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EXTENDING LIMITS ON NEUTRAL HEAVY LEPTONS

Michael Gronau *

Department of Physics, Syracuse University

Syracuse, N.Y. 13210

C. N. Leung

Fermi National Accelerator Laboratory ‡

P.O. Box 500, Batavia, IL 60510

and

Jonathan L. Rosner

Enrico Fermi Institute and Department of Physics

5640 S. Ellis Avenue, University of Chicago

Chicago, IL 60637

ABSTRACT

Neutral leptons corresponding to "right-handed neutrinos" are expected in many grand unified theories of the electroweak and strong interactions. At present the experimental limits on the masses and mixings with ordinary neutrinos of these leptons are very poor for masses above about 1 GeV. Suggestions are made for extending these limits, in experiments involving the production of b quarks, W and Z bosons, and any heavier gauge bosons that might exist, and via high-statistical studies of neutral current neutrino interactions.

*On leave from the Technion (Israel Institute of Technology), Haifa, Israel.

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I. INTRODUCTION

All the observed particles except neutrinos have both left-handed and right-handed versions. The neutrinos have been observed only in left-handed form. It is not clear whether this stems from a fundamental handedness of the weak interactions alone, or reflects some basic asymmetry in the spectrum. From the standpoint of theories which seek to unite quarks and leptons, the latter point of view appears most plausible. Thus, in the simplest of such "grand unified theories" (GUTs), based on the group SU(5), [1] the simplest representations containing all the known charged fermions only can accommodate a left-handed neutrino. If these representations are combined into a single irreducible representation of a higher group, such as SO(10), [2] a natural place for the right-handed neutrino arises, but its mass is by no means guaranteed to be the same as that of its left-handed partner. Indeed, there are both theoretical and experimental arguments that if such a neutral lepton exists, it must be relatively heavy. [3].

In the present paper, we explore the present limits on neutral heavy leptons which may undergo small mixings with the ordinary neutrinos. We find that these limits tend to be rather strict only for masses below about a GeV, implying mixings that are quite small. For masses above about 1 GeV, the limits deteriorate. We suggest several types of experiment for remedying this situation.

The study of neutral heavy leptons began in earnest about 10 years ago. [4] Since then, there has been a good deal of effort devoted to the study of their properties and corresponding experimental searches.[5] Thus, in some sense, we are reopening an old question. We do so because of the large number of experimental possibilities that have appeared in recent years for extending the range of searches for such objects. High-statistics neutrino experiments, production of b quarks, and studies of W and Z (and any heavier gauge boson) decays all can play a significant role in such searches. The possibility of multi-TeV hadron-hadron collisions in principle can even extend these searches up to lepton masses of many TeV, as we shall show. In planning multi-purpose detectors for present and future colliding beam machines, it is important not to miss possible signatures at neutral heavy leptons.

Our discussion will focus on neutral leptons which mix with neutrinos essentially instantaneously as a result of the large mass difference between the species. Thus our treatment is complementary to the study of neutrino oscillations. We shall be concerned primarily with direct searches for heavy leptons that do not depend on their having Majorana masses. As has been pointed out in Ref. 6, a number of interesting consequences (such as neutrinoless double beta-decay and wrong-sign leptons) are specific to the presence of Majorana masses in the theory.

We shall present a number of analyses which are meant primarily to indicate possibilities for useful experiments. They should not be taken as substitutes for detailed Monte Carlo calculations based on specific apparatus.

In Section II we present a simple model for mixing of neutral heavy leptons with ordinary neutrinos. This model contains the essential features of several descriptions of neutrinos already in the literature. [7-9] The model involves both neutral- and charged-current couplings of the neutral heavy leptons. A variant with only charged-current couplings is also discussed briefly. Universality of electron and muon neutrinos constrains the mixings to be small, corresponding to less than 10% in amplitude. The mixings can be larger for the tau neutrino. Lifetimes and branching ratios are estimated and general experimental signatures are noted.

Present mass and mixing limits are described in Section III. These are based on such experiments as direct low-mass searches [10] (e.g., in kaon decays), the absence of forward neutral decaying particles in neutrino beams from conventional sources or beam dumps, [11] and high-statistics neutrino experiments.

Stringent limits on mixing parameters come from searches for charmed particle semileptonic or leptonic decays to heavy leptons. Analyses in terms of b production can extend these limits upward in mass for certain ranges of mixings. The kinematic limit for such decays defines the maximum mass for which such searches are sensitive. We then go beyond present experiments to suggest extensions of the range of mixing and mass parameters for which useful bounds on heavy neutral leptons can be set. An "ideal" beam dump experiment for production of hadrons containing b quarks is described. Other sources of b quarks (e.g., in e^+e^- annihilations) also can be useful in setting limits. We also describe how the decays of W and Z bosons can help to search for heavy neutral leptons, and mention some possibilities at multi-TeV colliding hadron machines if new gauge bosons can be produced.

Our conclusions and a discussion of some alternative suggestions for heavy lepton searches, are contained in Section IV.

II. MIXING OF LIGHT AND HEAVY NEUTRAL LEPTONS

A. Assumptions.

In the standard picture of electroweak interactions, the charged and neutral weak current involving neutrinos are of the form

$$J^{\mu}_{CC} = \bar{\nu}_{eL}\gamma^{\mu}e_L + \bar{\nu}_{\mu L}\gamma^{\mu}\mu_L + \bar{\nu}_{\tau L}\gamma^{\mu}\tau_L \tag{2.1}$$

$$J^{\mu}_{NC} = \bar{\nu}_{eL}\gamma^{\mu}\nu_{eL} + \bar{\nu}_{\mu L}\gamma^{\mu}\nu_{\mu L} + \bar{\nu}_{\tau L}\gamma^{\mu}\nu_{\tau L} \tag{2.2}$$

The neutrinos are weak isodoublet members.

In many grand unified theories of the electroweak and strong interactions, *additional heavy neutral leptons occur which are primarily isosinglets under* ordinary weak SU(2). However, these can mix with the light neutrinos in such a way that the fundamental weak isodoublets entering into (2.1) and (2.2) acquire some admixture of the heavy states. This happens in two types of model of which we are aware, one with light (but not massless) neutrinos [3] and the other with strictly massless neutrinos [7-9]. In either case, a simple approximation to the charged and neutral currents may be obtained by replacing

$\nu_{iL}(i=e,\mu,\tau)$ in (2.1) and (2.2) by

$$\nu_{iL} \to N_{iL} \approx \nu_{iL}(1 - \sum_a |U_{ia}|^2/2) + \sum_a U_{ia}N_{aL} \tag{2.3}$$

Here the sum is over heavy lepton species a. The weak eigenstate is now N_{iL}; mass eigenstates are ν_i (light) and N_a (heavier). As we shall see presently, weak universality constrains the U_{ia}.

The model (2.3) in which light neutrinos simply mix with heavy ones will be *considered for the rest of this paper. Here we would like to simply point out* some other alternative possibilities at the outset.

In a model in which a neutrino mixes with another isodoublet, one can expect a suppression of flavor-changing neutral currents analogous to that which holds for quarks. By contrast, the substitution (2.3) will lead to both charged <u>and</u> neutral currents connecting the new heavy leptons with the familiar, lighter ones. Some of the bounds we shall obtain depend on the existence of these neutral currents.

We do <u>not</u> consider mixing of the known isodoublet neutrinos with higher isodoublet states (sequential leptons). We would expect the first evidence for such new states to come from decays of their corresponding charged lepton partners, *from neutrino-counting via measurement of the Z_0 total decay width, or* (for massive states) directly in Z^0 decays. (See R. Thun, Ref. 5).

We shall also not concern ourselves with the possibility of mixing among light neutrinos, in the absence of any present evidence for neutrino oscillations. The mixing (2.3) also will lead to oscillations, but of undetectably short wavelength for the masses of N_a we shall consider.

B. Specific mixing models.

1. Massive-neutrino model.

We shall consider for simplicity a version of the model first suggested in Ref. 3 in which each light neutrino mixes only with a single heavy lepton. Then the neutrino and heavy lepton are eigenstates of the mass matrix

$$M_i = \begin{bmatrix} 0 & \mu_i \\ \mu_i & M_{N_i} \end{bmatrix}, \qquad i=e,\mu,\tau, \tag{2.4}$$

(we assume $M_{N_i} >> \mu_i$), with

$$\nu_i \approx \begin{bmatrix} 1 - \mu_i^2/2M_{N_i}^2 \\ -\mu_i/M_{N_i} \end{bmatrix} \quad (\text{mass} \approx \mu_i^2/M_{N_i}) \tag{2.5}$$

$$N_i \approx \begin{bmatrix} \mu_i/M_{N_i} \\ 1 - \mu_i^2/2M_{N_i}^2 \end{bmatrix} \quad (\text{mass} \approx M_{N_i}) \tag{2.6}$$

Here μ_i is a Dirac mass, while M_{N_i} is a Majorana mass.

The mixing parameters U_{ia} in Eq. (2.3) are thus

$$U_{iN_i} \simeq -\mu_i/M_{N_i} \tag{2.7}$$

The inverse proportionality of U to the heavy lepton mass is a general feature which may prove important in evaluating the quality of a given search experiment. The mass μ_i is a typical Dirac mass. In grand unified theories it is often related to the corresponding mass of an $I_{3W} = +1/2$ quark (u,c,t), divided by ≈ 3 to account for renormalization-group corrections. [9,12] Thus (given a factor of 3 uncertainty in such estimates), we would take

$$\mu_e = (m_u/3)3^{\pm 1} = 0.5\text{-}5 \text{ MeV}, \tag{2.8}$$

$$\mu_\mu = (m_c/3)3^{\pm 1} = 150\text{-}1500 \text{ MeV}, \tag{2.9}$$

$$\mu_\tau = (m_t/3)3^{\pm 1} = 2.5\text{-}25 \text{ GeV}, \tag{2.10}$$

where we have arbitrarily taken $m_t = 25$ GeV. (In the model of Ref. 6 , the value of μ is the corresponding charged lepton mass.) Given present bounds on neutrino masses [13,14]

$$m(\nu_e) \le 60 \text{ eV}; \quad m(\nu_\mu) \le 0.5 \text{ MeV}; \quad m(\nu_\tau) \le 250 \text{ MeV} \quad , \tag{2.11}$$

we would then predict

$$|U_{e\,N_e}| \le 10^{-4}; \quad |U_{\mu N_\mu}| \le 3\times10^{-3}; \quad |U_{\tau N_\tau}| \le 10^{-1} \quad , \tag{2.12}$$

and, correspondingly,

$$M_{N_e} \ge 4 \text{ GeV}, \quad M_{N_\mu} \ge 45 \text{ GeV}; \quad M_{N_\tau} \ge 25 \text{ GeV}. \tag{2.13}$$

The limits (2.12) are compatible with weak universality for the observed neutrinos. The limits (2.13) suggest that heavy leptons could be observed at present accelerators. Of course, if the muon and tau neutrinos are long-lived enough that their masses must satisfy cosmological upper bounds [15] of order 100 eV, the corresponding N_μ and N_τ must be much heavier. Then, only N_e would be accessible in laboratory experiments, and its mixing with ν_e according to Eq. (2.12) would be quite small.

The absolute values of $|U|^2$ implied by (2.7)-(2.10) are shown in Fig. 1a. Also shown are the bounds based on Eqs. (2.11) and (2.5)-(2.7), which imply $|U|^2 M_N = m_\nu \le m_\nu(\max)$ for each neutrino flavor.

The papers of Ref. 3 treated the case of very heavy N_i's, $M(N_i) \ge 100$ GeV or much heavier. In Eq. (2.13), we have relaxed these bounds somewhat. Moreover, it has recently been suggested [16] that N_i could be even lighter than the bounds (2.13), on the basis of freedom of the Yukawa coupling giving rise to μ_i. If this were true, the corresponding mixing parameters could be smaller than in Fig. 1a.

2. Massless-neutrino model.

The (light) neutrinos can be strictly massless as a result of some discrete symmetry. [7] Heavy neutral leptons are still present in such models. They can acquire Dirac masses as a result of mixing with additional weak isosinglets introduced for the purpose. [17] This behavior has been investigated in a model for three generations, with the result [9,18] (see Eq. (2.3))

$$N_{eL} \cong \nu_{eL}\left(1 - \frac{a_1^2}{2M_{N_2}^2}\right) + N_{2L}\,\frac{a_1}{M_{N_2}} \tag{2.14}$$

$$N_{\mu L} \cong \nu_{\mu L}\left(1 - \frac{a_1^2}{2M_{N_1}^2} - \frac{a_2^2}{2M_{N_3}^2}\right)$$

$$+ N_{1L}\left(\frac{a_1}{M_{N_1}}\right) + N_{3L}\left(\frac{a_2}{M_{N_3}}\right) \tag{2.15}$$

$$N_{\tau L} \cong \nu_{\tau L}\left(1 - \frac{a_2^2}{2M_{N_2}^2} - \frac{a_3^2}{2M_{N_3}^2}\right) + N_{2L}\left(\frac{a_2}{M_{N_2}}\right)$$

$$+ N_{3L}\left(\frac{a_3}{M_{N_3}}\right) \tag{2.16}$$

The parameters a_i have been estimated in terms of Dirac masses of u, c, t quarks:

$$a_1 \approx [(m_u m_c)^{1/2}/3] \times 3^{\pm 1} = 10\text{-}100 \text{ MeV} \tag{2.17}$$

$$a_2 \approx [(m_t m_c)^{1/2}/3] \times 3^{\pm 1} = 0.6\text{-}6 \text{ GeV} \tag{2.18}$$

$$a_3 \approx [(m_t - m_c + m_u)/3] \times 3^{\pm 1} = 2.5\text{-}25 \text{ GeV} \tag{2.19}$$

The mixings (2.14)-(2.16) imply violations of weak universality for processes involving light neutrinos. These are discussed from a model-independent standpoint in the next subsection. The results are

$$\sum_a |U_{eN_a}|^2 \le 4.3\% \tag{2.20}$$

$$\sum_a |U_{\mu N_a}|^2 \le 0.8\% \tag{2.21}$$

$$\sum_a |U_{\tau N_a}|^2 \le 10\% \text{ (anticipated)} \tag{2.22}$$

The ranges (2.17)- (2.19) and the bounds (2.20)-(2.22) then lead to the allowed regions of $|U|^2$ and M_N shown in Fig. 1b. The corresponding bounds on lepton masses are:

$$M_{N_1} \gtrsim 0.1 \text{ GeV} \quad \text{(improved below)} \tag{2.23}$$

$$M_{N_2} \gtrsim 2 \text{ GeV (anticipated)} \tag{2.24}$$

$$M_{N_3} \gtrsim 8 \text{ GeV (anticipated)} \tag{2.25}$$

These results, in contrast to Eq. (2.13), are open to a much wider range of tests based on present experiments. Notice in Eqs. (2.14)-(2.16) that just as in the massive-neutrino model, the mixing parameters U_{ia} are inversely proportional to the heavy lepton masses M_{N_a}. The bound (2.23) will be replaced by a stronger one ($\gtrsim 1$ GeV) presently. The possibility of a variety of neutral heavy leptons in the 1-10 GeV range suggests a large number of possible experimental tests. While many of these have been emphasized previously [4,5], some of the relevant experiments are just now becoming possible.

C. Model-independent universality constraints.

In the two models presented in subsection B, the coupling of the ith light neutrino ν_i to the charged and neutral weak currents is diminished by a factor $1-\frac{1}{2}\sum_a |U_{ia}|^2$, as noted in Eq. (2.3). In Ref. 9, constraints on this parameter arising from weak universality have been presented. These are now summarized and, where appropriate, extended.

1. Comparison of $^{14}O \to {}^{14}Ne\nu$ and $\mu \to e\nu\bar{\nu}$.

If V_{ud} denotes the charged-current matrix element between u and d, this comparison implies [19]

$$|V_{ud}| \Big/ \left(1-\frac{1}{2}\sum_a |U_{\mu N_a}|^2\right) = 0.9737 \pm 0.0025. \tag{2.26}$$

Unitarity of the Kobayashi-Maskawa matrix and information on s, b decays and charmed-particle production in neutrino reactions provides an upper bound on $|V_{ud}|$. This bound has improved somewhat as a result of recent data. The new ingredients since the analysis of Ref. 9 include measurement of the b lifetime, [20] which we may use to conclude $|V_{bc}| \leq 0.065$, [21], and the improved limit $|V_{bu}/V_{bc}| < 0.15$ coming from the study of leptons in b decay. [22] The result is

$$|V_{ud}| \geq 0.9748 \quad (2\sigma \text{ level}), \tag{2.27}$$

which, when combined with Eq. (2.26), leads to

$$\sum_a |U_{\mu N_a}|^2 \leq 0.8\% \quad (2\sigma \text{ level}). \tag{2.28}$$

2. τ lifetime.

The prediction of weak universality is

$$\tau_\tau^{th} = (2.8 \pm 0.2) \times 10^{-13} \text{ s}, \tag{2.29}$$

where the error comes from uncertainties in the experimental $\nu_\tau e \nu$ and $\nu_\tau \mu \nu$ branching ratios. [23] A new measurement [24] gives

$$\tau_\tau^{exp} = (3.20 \pm 0.41 \pm 0.35) \times 10^{-13} \text{ s}. \tag{2.30}$$

Deviations from weak universality may be gauged from

$$\frac{\tau_\tau^{th}}{\tau_\tau^{exp}} = 1 - \sum_a |U_{\tau N_a}|^2. \tag{2.31}$$

Present comparison of (2.29) and (2.30) only constrains $\sum_a |U_{\tau N_a}|^2$ to be less than about 30%. Let us anticipate improvements in this figure such that

$$\sum_a |U_{\tau N_a}|^2 \leq 10\% \quad (\text{anticipated}). \tag{2.32}$$

In what follows, we shall use this estimate, keeping in mind that it has not yet been attained. Precise τ lifetime measurements thus continue to be of considerable importance.

3. Comparison of $\pi \to e\nu$ and $\pi \to \mu\nu$.

Lepton masses, radiative corrections, and neutrino mixings combine to give the prediction [25]

$$R \equiv \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} = (1.233 \times 10^{-4}) \, \frac{1 - \sum_a |U_{eN_a}|^2}{1 - \sum_a |U_{\mu N_a}|^2}. \tag{2.33}$$

Experimentally [26]

$$R = (1.218 \pm 0.014) \times 10^{-4}. \tag{2.34}$$

Thus

$$-0.035 \leq \sum_a |U_{\mu N_a}|^2 - \sum_a |U_{eN_a}|^2 \leq 0.011 \ (2\sigma). \tag{2.35}$$

Combining (2.35) with (2.28), we find only

$$\sum_a |U_{eN_a}|^2 \leq 4.3\% \tag{2.36}$$

D. Lifetime estimates

In Fig. 2 we show typical decay mechanisms for a neutral heavy lepton. Both charged and neutral weak currents can contribute. The rate for any given process scales as M_N^5.

In Ref. 9 a rough attempt was made to estimate the rate at which new decay channels open up as M_N increases. The total decay rate from charged-and neutral-current processes may be expressed in terms of $\Gamma_\mu = 4.55 \times 10^5 \text{ s}^{-1}$:

$$\frac{\Gamma_N}{\Gamma_\mu} = \sum_\ell |U_{\ell N}|^2 \left(\frac{M_N}{M_\mu}\right)^5 \Phi_\ell(M_N), \tag{2.37}$$

where the effective number Φ of unit-strength charged-current channels may be calculated straightforwardly. (In similar fashion one would find $\Phi = 5$ for τ decays: 1 for $e\nu$, 1 for $\mu\nu$, and 3 for $u\bar{d}$). Thresholds were estimated crudely (with arbitrary weights 0, $\frac{1}{2}$, or 1). The resulting estimate of Φ from 2 to 50 GeV was fit with a power-law:

$$\Phi(M_N) = N_0 \, (M_N / 1 \text{ GeV})^p. \tag{2.38}$$

The power-law obtained in Ref. 9 corresponds to p=0.3. Here we calculate the opening of new channels more precisely with the help of exact matrix elements and phase space for three-body final states produced in charged-current and neutral current decays. These matrix elements and phase space factors lead to the following finite mass suppression factors I for the decay process $A \rightarrow B + C + \bar{D}$:

i) A-B and C-D couplings left-handed: [27]

$$I = I_1\left(\frac{M_B}{M_A}, \frac{M_C}{M_A}, \frac{M_D}{M_A}\right), \tag{2.39}$$

where

$$I_1(x,y,z) = 12\int_{(x+y)^2}^{(1-z)^2} \frac{ds}{s}(s-x^2-y^2)(1+z^2-s)$$

$$\times\left\{[s-(x-y)^2][s-(x+y)^2][(1+z)^2-s][(1-z)^2-s]\right\}^{1/2}. \tag{2.40}$$

(Note that I(0,0,0) = 1.)

ii) A-B and C-D couplings right-handed: [27]

$$I = I_1\left(\frac{M_B}{M_A}, \frac{M_D}{M_A}, \frac{M_C}{M_A}\right). \tag{2.41}$$

iii) A-B couplings right-handed and C-D couplings left-handed (or vice versa):

$$I = I_2\left(\frac{M_B}{M_A}, \frac{M_C}{M_A}, \frac{M_D}{M_A}\right), \tag{2.42}$$

where

$$I_2(x,y,z) = 24\,yz\int_{(y+z)^2}^{(1-x)^2} \frac{ds}{s}(1+x^2-s)$$

$$\times\left\{[(1+x)^2-s][(1-x)^2-s][s-(y+z)^2][s-(y-z)^2]\right\}^{1/2}. \tag{2.43}$$

We consider three limiting cases, in which the heavy lepton mixes primarily with ν_e, ν_μ, or ν_τ. In all cases charged-current decays contribute exclusively to some processes, neutral-current decays exclusively to some others, and an

interference between charged-and neutral-current decays occurs in still others. For example, a neutral lepton mixing exclusively with ν_e decays to $\nu_e e^+e^-$ via both charged and neutral current. This interference is taken into account in calculating total rates.

The assumed masses, in addition to those measured for the charged leptons, are $m_u = m_d = 10$ MeV, $m_s = 0.15$ GeV, $m_c = 1.5$ GeV, $m_b = 5$ GeV, and $m_t = 25$ GeV. We take $\sin^2\theta_W = 0.22$ in calculating neutral-current decays.

The resulting factors Φ_i for heavy leptons mixing with light neutrinos $\nu_i (i=e,\mu,\tau)$ are shown in Fig. 3. A best-fit to the form (2.38) yields:

$$\Phi_e(M_N) = 6.95\,(M_N/1\,\mathrm{GeV})^{0.17} \tag{2.44}$$

$$\Phi_\mu(M_N) = 6.41\,(M_N/1\,\mathrm{GeV})^{0.19} \tag{2.45}$$

$$\Phi_\tau(M_N) = 2.66\,(M_N/1\,\mathrm{GeV})^{0.44}. \tag{2.46}$$

The corresponding lifetimes are predicted to be

$$\tau_{N_e} = 4.15\times10^{-12}\,\mathrm{s}\,(M_N/1\,\mathrm{GeV})^{-5.17}\,|U|^{-2} \tag{2.47}$$

$$\tau_{N_\mu} = 4.49\times10^{-12}\,\mathrm{s}\,(M_N/1\,\mathrm{GeV})^{-5.19}\,|U|^{-2} \tag{2.48}$$

$$\tau_{N_\tau} = 1.08\times10^{-11}\,\mathrm{s}\,(M_N/1\,\mathrm{GeV})^{-5.44}\,|U|^{-2}. \tag{2.49}$$

We restrict the discussion to $M_N \lesssim 50$ GeV. Above this value, W and Z propagator effects begin to be important, and for $M_N > M_W, M_Z$ decays to real W's and Z's dominate, with rates

$$\Gamma(N\to W\ell) = \frac{G_F M_W^2}{4\pi\sqrt{2}} M_N |U_{N\ell}|^2 \times\left\{1-\frac{M_W^2}{M_N^2}\right\}^2\left\{1+\frac{1}{2}\frac{M_N^2}{M_W^2}\right\}, \tag{2.50}$$

$$\Gamma(N\to Z\nu_\ell) = \frac{G_F M_Z^2}{8\pi\sqrt{2}} M_N |U_{N\ell}|^2 \times\left\{1-\frac{M_Z^2}{M_N^2}\right\}^2\left\{1+\frac{1}{2}\frac{M_N^2}{M_Z^2}\right\}. \tag{2.51}$$

Thus the approximate forms (2.47)-(2.49) are no longer valid for very high-mass neutral leptons N.

The branching ratios of heavy leptons into various final states are shown in Fig. 4. Typical values are

$$B(N \to \ell^+ \ell^{-\prime} \nu) \simeq 0.2 \tag{2.52}$$

$$B(N \to \text{neutrinos}) \simeq 0.2 - 0.1 \tag{2.53}$$

$$B(N \to \ell^- + \text{hadrons}) \simeq 0.4 - 0.5 \tag{2.54}$$

$$B(N \to \nu + \text{hadrons}) \simeq 0.2 \,. \tag{2.55}$$

The decay mode (2.54) is useful in principle for reconstructing the mass of N. For low-mass leptons, Table 1 gives a more detailed breakdown.

As an illustration of the range of lifetimes one may expect, we show in Fig. 5 contours of fixed τ_N from Eq. (2.48) as a function of $|U|^2$ and M_N. These may be compared if desired with Figs. 1 to see the enormous range of possibilities allowed in specific models.

In left-right symmetric models there is another potential source of N decay, which involves the exchange of a right-handed W. The N then couples to a charged lepton with full strength, so there is no mixing factor $|U|^2$ in the decay rate. On the other hand, the rate is suppressed with respect to that for an ordinary weak charged-current decay by the factor $(M_{W_L}/M_{W_R})^4$. The W_R can couple with full strength to right-handed quark pairs: $(u,d)_R$; $(c,s)_R$; $(t,b)_R$. Thus the effective number of open channels is not very different from that illustrated in Figs. 3; it is 3 for each fully open quark isodoublet channel.

The decay of N via a right-handed W then predominates over its decay via mixing with a left-handed neutrino if

$$(M_{W_L}/M_{W_R})^4 \geq |U|^2 \,. \tag{2.56}$$

Bounds on M_{W_R} depend on the processes assumed, but one cannot in the present case use any bounds based on lepton-light neutrino charged currents. A bound based

on the $K_L - K_S$ mass difference [28] implies

$$M_{W_R} \gtrsim 1.6 \text{ TeV} , \tag{2.57}$$

and hence the decay via W_R only has a <u>chance</u> of predominating if

$$|U|^2 \leq \left(\frac{80 \text{ GeV}}{1.6 \text{ TeV}}\right)^4 \simeq 6 \times 10^{-6} \,. \tag{2.58}$$

If there are two <u>different</u> types of heavy lepton N_1 and N_2, coupled via W_R to charged leptons ℓ_1 and ℓ_2, decays of the form

$$N_1 \to \ell_1 N_2 \bar{\ell}_2 \tag{2.59}$$

also may occur via W_R exchange. These could give rise to interesting multi-lepton signatures, as discussed in Sec. III.D.

E. <u>Experimental signatures of a neutral heavy lepton</u>.

Fig. 5 shows that detectable path lengths are possible for quite a wide range of possible parameters. These paths range all the way from sub-millimeter tracks to hundreds of meters, depending on masses and mixings. In Sec. III we shall discuss specific experiments sensitive to these possibilities. Here we give a brief overview.

Since a neutral heavy lepton decays by mixing with light neutrinos, its decay products must contain either a charged lepton (if it decays via the charged current) or a neutrino (if it decays via the neutral current). The weak current then materializes into a lepton pair or a quark pair, as illustrated in Fig. 2.

For 1 GeV $\lesssim M_N \lesssim$ 2 GeV, one can expect the weak current to give rise to a restricted class of hadronic final states, just as in τ decay. Thus we might expect to see

$$N \to \ell^- u \bar{d} \tag{2.60}$$

appearing in the forms

$$N \to \ell^- \pi^+$$
$$\ell^- \pi^+ \pi^0$$
$$\ell^- \pi^+ \pi^+ \pi^- \quad . \qquad (2.61)$$

For heavier N, exclusive final states will become harder to reconstruct as the number of different channels grows. However, calorimetric methods based on jet reconstruction could in principle measure even very high effective masses.

A neutrino beam can produce heavy neutral leptons via a neutral-current interaction. These can then travel some distance from the interaction point, or be detected immediately. Events can be scanned for secondary vertices, for unusual leptons or lepton energies, or even for decay leptons from upstream interactions. Some possibilities are summarized in Table 2.

Heavy quarks such as c and b can decay semileptonically via the charged weak current to a neutral heavy lepton and a charged lepton. Thus one might examine events with c or b production for secondary vertices or unusual leptons. As we shall see, only a restricted set of mixings may be possible for heavy leptons that can be produced in c decays. A dedicated experiment with many b quarks produced could set some very useful limits on neutral heavy leptons in new regions of mass and mixing.

If W or Z bosons decay occasionally to neutral heavy leptons, one might see signatures very similar to $W \to \ell\nu$ or $Z \to \nu\bar{\nu}$ except for the presence of secondary vertices. This also holds for heavier W's and Z's if they exist, with the added possibility of full-or nearly full-strength couplings to eN or $N\bar{N}$ for some varieties of such W's and Z's.

III. PRESENT AND FUTURE MASS AND MIXING LIMITS

A. Leptons from π, K decay.

The absence of N coupled to μ or e in π, $K \to \mu N$ or π, $K \to eN$ has been demonstrated directly in dedicated search experiments [10] and indirectly via the absence of decays downstream of accelerator neutrino sources. [29] If any neutral leptons exist with masses less than $M_K - M_\ell$ (ℓ=e or μ), their mixings with ν_ℓ must be extremely small: typically $|U|^2 \lesssim 10^{-5} - 10^{-6}$, depending somewhat on the mass. Such small values are implausible in the specific models illustrated in Fig. 1, though they could arise in the version of Ref. 16.

B. Exotic τ decays.

Some time ago it was suggested that the decays $\tau \to \nu_\tau N e$ or $\tau \to \nu_\tau N \mu$ could be used to search for new neutral leptons coupled with full strength to electrons or muons. [30] A search [31] excluded such leptons up to about 1.2 GeV in mass. However, the statistics were too limited to exclude neutral leptons coupling with reduced strengths. A more recent search for unexpected τ decay modes [32] involves final states without ν_τ. If $\tau \to N_\tau + \cdots$, and N_τ decays via mixing primarily to ν_τ, there will still appear a ν_τ in the final state. Thus this search cannot help set limits except under special circumstances for the present class of models.

C. Beam dump production of c and b quarks.

Neutral heavy leptons can be produced in hadronic interactions from the decays of c and b quarks: e.g.,

$$D^{+}_{0} \to [S = -1] + N + (\text{lepton})^+ \qquad (3.1)$$

$$D^\pm,\ F^\pm \to N + (\text{lepton})^\pm \qquad (3.2)$$

$$B^0 \to [\text{charm}] + \bar{N} + (\text{lepton})^- \quad . \qquad (3.3)$$

Several beam dump experiments are sensitive to N at a useful level. We first estimate the rates for charm and b production and for charm and b decay into a neutral heavy lepton.

1. Production rates.

Many of the experiments we shall discuss were performed at an incident proton energy of 400 GeV. For this energy, the cross section for charm production has been measured to be [33]

$$\sigma(p + \text{nucleon} \to D\bar{D} + \cdots) = 27 \pm 4 \pm 5 \ \mu b \tag{3.4}$$

for $d^3\sigma/dp^3 \sim (1-x)^4 e^{-2m_\perp}$, $m_\perp = (p_\perp^2 + m_D^2)^{1/2}$ in GeV.

The cross section for hadronic F production has not yet been measured. In analogy with strange particle production, we might guess that it is about 1/10 of that for D production. As we shall see below, even at this level F's could be a potential source of useful information on heavy leptons.

For an estimate of hadronic B production, we scale the cross section for charm production at a lower value of $\sqrt{s}$:

$$\sigma(B\bar{B}\,;\sqrt{s}) \simeq \left(\frac{m_D}{m_B}\right)^2 \sigma\left(D\bar{D}\,;\sqrt{s}\,\frac{m_D}{m_B}\right). \tag{3.5}$$

We assume, as in Ref. 33, that the charm cross section behaves as $s^{1.3}$, so that

$$\sigma(B\bar{B}\,;\sqrt{s}) \simeq (m_D/m_B)^{4.6}\,\sigma(D\bar{D}\,;\sqrt{s}). \tag{3.6}$$

A slightly more pessimistic estimate results if we replace (3.5) by the assumption [34] that cross sections scale as Γ_h/M^3, where Γ_h is a two-gluon hadronic width. If Γ_h varies slowly with M (as is true for the three-gluon widths of ψ and Υ), the power in (3.6) could be as large as 5.6. We then estimate (at p_L = 400 GeV/c)

$$\sigma(B) + \sigma(\bar{B}) \gtrsim 10^{-31}\ cm^2. \tag{3.7}$$

Halzen [34,35] has obtained the estimate 10^{-32} cm^2 for the non-diffractive component of B production. We shall present results for both 10^{-31} cm^2 and 10^{-32} cm^2 in the absence of a firm measurement of this quantity. [36]

2. Charm and b decays to N.

The cross section (3.4) was obtained from the semileptonic decays of charmed particles under the assumption that $D\bar{D}$ production dominated, and that the average semileptonic branching ratio was that measured in e^+e^- annihilations at the ψ'': [37]

$$\bar{B}_{SL}(D) = 8.2 \pm 1.2\,\%. \tag{3.8}$$

The rate for the process (3.1) may be related to that for ordinary semileptonic decay via the kinematic factor $I_1\left(\frac{m_s}{m_c}, \frac{M_N}{m_c}, \frac{m_\ell}{m_c}\right)$, defined in Eq. (2.40) and plotted in Fig. 6. Then

$$\bar{B}(D \to [s=-1]N\ell^+) = \bar{B}_{SL}(D)\,\frac{I_1\left(\frac{m_s}{m_c}, \frac{M_N}{m_c}, \frac{m_\ell}{m_c}\right)}{I_1\left(\frac{m_s}{m_c}, 0, \frac{m_\ell}{m_c}\right)}\,|U|^2. \tag{3.9}$$

The purely leptonic decays of D^+ and F^+ are potential sources of more massive neutral leptons. The estimates of these branching ratios follow standard methods. [4,30] Here we assume that N mixes with ν_e. For mixing with ν_μ, the kinematic limit on the highest accessible N mass is simply about 100 MeV less. We find

$$\Gamma(D^+ \to Ne^+) = |U|^2\,\Gamma(K \to \mu\nu)\,(f_D/f_K)^2 \times \frac{M_N^2\,m_D}{m_\mu^2\,m_K}\left[\frac{1 - M_N^2/m_D^2}{1 - m_\mu^2/m_K^2}\right]^2 ; \tag{3.10}$$

$$\Gamma(F^+ \to Ne^+) = |U|^2 \cot^2\theta_c\,\Gamma(K \to \mu\nu)\,(f_F/f_K)^2 \times \frac{M_N^2\,m_F}{m_\mu^2\,m_K}\left[\frac{1 - M_N^2/m_F^2}{1 - m_\mu^2/m_K^2}\right]^2 \tag{3.11}$$

As a conservative estimate we take $f_D = f_F = f_K$. [38] The measured lifetimes of D^+ and F^+ are [39]

$$\tau_{D^+} = (8.2\ {}^{+1.2}_{-1.0}) \times 10^{-13}\ s, \tag{3.12}$$

$$\tau_{F^+} = (2.5\ {}^{+1.2}_{-0.7}) \times 10^{-13}\ s. \tag{3.13}$$

We assume central values. Then, for m_F = 1.97 GeV, [40]

$$B(D^+\to Ne^+) = (1.57\times 10^{-2})|U|^2 (M_N/1\,GeV)^2 [1-M_N^2/m_D^2]^2 ; \tag{3.14}$$

$$B(F^+\to Ne^+) = 10^{-1}|U|^2 (M_N/1\,GeV)^2 [1-M_N^2/m_F^2]^2 . \tag{3.15}$$

The semileptonic and leptonic branching ratios (3.9), (3.14), and (3.15) are compared with one another in Fig. 7. For M_N above 0.8 GeV, leptonic decays of D^+ provide an intrinsically larger branching ratio. However, since D^+ production is certainly no more than half and probably more like a third of hadronic D production, the advantage of the leptonic decays probably is only felt for M_N above about 1 GeV. For 1 GeV $\le M_N \le$ 1.7 GeV, the $F^+\to Ne^+$ branching ratio is larger than that of $D^+\to Ne^+$ by about the same amount that one might expect F^+ production to be suppressed. Hence F^+ production, once measured, is likely to add statistical power to a heavy lepton search, and will allow the mass range to be extended by about 100 MeV.

The branching ratio of B (hadrons containing b quarks) to heavy leptons in Eq. (3.3) may be estimated from the integral $I_1\left(\frac{m_c}{m_b},\frac{m_\ell}{m_b},\frac{M_N}{m_b}\right)$ in Eq. (2.40), plotted in Fig. 8. For future reference we also show the average value of P_N/M_N in the B center-of-mass. When $M_N=0$, the process (3.3) corresponds to $b\to ce^-\bar{\nu}_e$, which is measured to have a branching ratio of 11.6 ± 0.5% ≡ $\bar{B}_{SL}(B)$. [22] Then

$$\bar{B}(B\to[\text{charm}]\ell^-\bar{N}) = \bar{B}_{SL}(B)\frac{I_1\left(\frac{m_c}{m_b},\frac{m_\ell}{m_b},\frac{M_N}{m_b}\right)}{I_1\left(\frac{m_c}{m_b},\frac{m_\ell}{m_b},0\right)}|U|^2 . \tag{3.16}$$

The result is shown in Fig. 9. The absence of any detectable $b\to u$ coupling prevents us from making an estimate of leptonic decays of $b\bar{u}$ mesons, but such decays will be quite rare and probably of no use in setting bounds on neutral heavy leptons.

3. General experimental considerations.

After the heavy lepton is produced via charm or b decay, it travels a

distance

$$L = P_N c\tau_N / M_N , \tag{3.17}$$

with τ_N estimated via one of Eqs. (2.47) - (2.49). The lifetime τ_N depends on the mixing strength $|U|^2$, and can be quite long for small $|U|^2$. This can help in detection.

The beginning of the decay region is assumed to be a distance ℓ_1 from the point of production, and the length of the decay region is Δ. Then the probability P_d that N is observed to decay between ℓ_1 and $\ell_1+\Delta$ from the target is

$$P_d = e^{-\ell_1/L}\left(1-e^{-\Delta/L}\right) . \tag{3.18}$$

A specific experiment with angular acceptance ϵ_Ω thus will set limits on $|U|^2$ and M_N corresponding to a fixed value of

$$\sigma(D \text{ or } B)\, B(D \text{ or } B\to N)\, B(N\to \text{detected mode})\; P_d\; \epsilon_\Omega . \tag{3.19}$$

There have been several beam-dump experiments sensitive to heavy lepton production in the past few years. [41-48] Some of them are summarized in Table 3. The most recent in this table has quoted a limit on D decay to a heavy lepton based on the process $D\to Ne^+$. In what follows we shall present an independent analysis of this experiment, extending it to the case of B production. We hope that this illustrative example can encourage the analysis of some of the other experiments in Table 3 in terms of charm and B decay, as well as stimulating further searches in beam dumps.

4. The CHARM experiment.

In Fig. 10 we reproduce the limit quoted by Winter [48] on a neutral heavy lepton N mixed with ν_e, on the basis of the decay $D\to eN$, $N\to e^+e^-\nu_e$. The lower curve corresponds to long-lived leptons, while the limitation set by the upper curve arises when the leptons decay before reaching the detector.

We now present a parallel analysis of the CHARM experiment, both in terms of $D^{\pm} \to Ne^{\pm}$ and in terms of $B \to (\text{charm})\, e^{\pm} N$. Our results from $D \to Ne$ do not exclude quite as large a region of the $|U|^2$- M_N plane as that shown in Fig. 10, but are qualitatively similar. We thus feel that our estimates based on b production may err, if at all, on the conservative side.

The quantities required for the $D \to Ne$ analysis include: (a) the D production cross section and x, $p^{\perp}$ distribution; (b) the branching ratio $B(D \to Ne)$ as a function of M_N; (c) the branching ratio $B(N \to e^+e^-\nu_e)$ (since the e^+e^- final state is what is searched for); (d) the angular acceptance ϵ_{Ω}, and (e) the probability that a lepton traversing the detector will decay within it. For analysis in terms of B production, the quantities (a) and (b) are replaced by (a') the b or $\bar{b}$ production cross section, and (b') the branching ratio $b \to c\, Ne^-$. We shall also describe the limits that might be obtained from an "ideal" beam dump experiment.

(a) $D^{\pm}$ production. Some D mesons are produced "directly"; others occur via cascades from D^*. We shall assume that $\sigma(D, \text{direct}) = \sigma(D^*)$. Then since D^* decays favor D° by a known amount, we find $\sigma(D^+ \text{ or } D^-) \simeq (D^\circ \text{ or } \bar{D}^\circ)/2$, and with the help of (3.4) we estimate for protons at p_L = 400 GeV that

$$\sigma(D^+) + \sigma(D^-) = 18\ \mu b\ . \tag{3.20}$$

In the CHARM beam dump experiment the total number of $D^{\pm}$ produced is then

$$N(D^+) + N(D^-) = \frac{18 \times 10^{-30}\ cm^2}{4 \times 10^{-26}\ cm^2} \times (2.4 \times 10^{18}) \simeq 10^{15}\ . \tag{3.21}$$

As noted earlier, charmed particles leading to direct leptons appear to be produced with a distribution [33,49]

$$d^3\sigma/dp^3 \sim (1-x)^4\ e^{-2m_\perp}\ ,$$
$$m_\perp \equiv (p_\perp^2 + m_D^2)^{1/2} \text{ in GeV}\ . \tag{3.22}$$

We shall thus take the average D produced at p_L = 400 GeV to have p_D = 67 GeV in the laboratory. The $m_\perp$ distribution will enter into our calculation performed below of geometric acceptance.

(b) $D \to Ne$ branching ratio. We assume for present purposes that N mixes primarily with ν_e with mixing parameter U. (Similar arguments apply to the mixing of N with ν_μ, but the kinematic limit on the highest accessible N mass is simply about 100 MeV less.) The branching ratio of interest is then that given by Eq. (3.14) and shown by the dashed curve in Fig. 7.

(c) $N \to e^+e^-\nu_e$ branching ratio. Again, we assume here that N mixes primarily with ν_e. The above decay then occurs via both charged and neutral currents. Taking account of the contribution of both of these, we find [9, 18] (for $M_N >> 2m_\mu$ and $\sin^2\theta_W = 0.22$)

$$\Gamma(N_e \to e^+e^-\nu_e)/\Gamma(N_e \to e\mu\nu) = 0.57. \tag{3.23}$$

The branching ratio to $\mu^+\mu^-\nu_e$ is much less:

$$\Gamma(N_e \to \mu^+\mu^-\nu_e)/\Gamma(N_e \to e\mu\nu) = 0.13\ . \tag{3.24}$$

If N mixes primarily with ν_μ, the above two estimates apply, respectively, to the $\mu^+\mu^-\nu_\mu$ and $e^+e^-\nu_\mu$ final states.

The total N_e decay rate and $e^+e^-\nu_e$ branching ratio were estimated in Sec. II.D. Referring to Table 1, we see that for the mass range of interest the branching ratio to $e^+e^-\nu_e$ is about 8%. We shall assume this number in what follows. If only charged currents contributed to N_e decay, this number would be about 20% instead, and the bounds would only be stronger.

(d) Geometric acceptance. From the parameters given in Ref. 47, one sees that the detector subtends 9.6% in azimuth, and a polar angle ranging from $\theta_1 \equiv 7.3$ mr to $\theta_2 \equiv 13.5$ mr. The total solid angle is then 3.9×10^{-5} sr. We assume that the average angle at which N is emitted is that of its parent particle, the D. Using the $p^{\perp}$ distribution (3.22), and an average D momentum of 67 GeV, we find that the polar angle acceptance is 0.19, and hence the angular acceptance is

$$\epsilon_\Omega = \epsilon_\theta \, \epsilon_\phi \simeq (1/5)(1/10) \simeq 2\% . \qquad (3.25)$$

We shall assume a constant figure of 2% in what follows.

(e) Longitudinal detection probability. Here we need $p_N^{\parallel}$. Assuming a D of momentum $\langle P_D^{\parallel} \rangle$ = 67 GeV, and standard two-body kinematics, we find that a uniform $D \rightarrow Ne$ decay distribution in the center-of-mass angle leads to a uniform distribution in longitudinal momentum. We calculate an average N momentum ranging from about 33 GeV for very light N to nearly 67 GeV for N near the kinematic limit:

$$\langle p_N^{\parallel} \rangle = \frac{\langle p_D^{\parallel} \rangle}{2} \left\{ 1 + \frac{M_N^2}{M_D^2} \right\} . \qquad (3.26)$$

The longitudinal acceptance of the detector is the probability P_d *that N* decays within a distance between ℓ_1 = 480 m and $\ell_1 + \Delta = \ell_1$ + 35 m from the target, where P_d is given by Eq. (3.18).

The resulting region of parameters excluded by the absence of a detectable decay $N \rightarrow e^+e^- + \ldots$ is shown by the solid curve in Fig. 11a. The experiment is sensitive up to near the kinematic limit. As mentioned earlier, information on F production could add to an extension of the excluded region.

A small additional region of small $|U|^2$ may be excluded by considering D semileptonic decays. The total number of D's in the experiment is about 3×10^{15}. The average momentum of N is taken for simplicity as 25 GeV; it is lower than *for 2-body D decay. The excluded region is bounded from below by the dotted* curve in Fig. 11a.

Now we estimate what improvement in bounds, if any, follows from analyzing the CHARM experiment in terms of b decays.

(a') B production. As mentioned earlier, we shall take two possibilities:

$$\sigma(B) + \sigma(\bar{B}) = \begin{cases} 10^{-31} \ \mathrm{cm}^2 \\ 10^{-32} \ \mathrm{cm}^2 \end{cases} \qquad (3.27)$$

for 400 GeV protons on nucleons. This leads us to expect

$$N(B) + N(\bar{B}) = \frac{10^{-31} \text{ to } 10^{-32} \ \mathrm{cm}^2}{4 \times 10^{-26} \ \mathrm{cm}^2} \times (2.4 \times 10^{18})$$

$$= \begin{cases} 6 \times 10^{12} \\ 6 \times 10^{11} \end{cases} . \qquad (3.28)$$

(b') $b \rightarrow cNe$ branching ratio. This quantity has been estimated above (Fig. 9).

(d') Geometric acceptance. Here we continue to assume the 2% figure discussed above.

(e') Longitudinal detection probability. The average momentum p_N^* of N in the B center-of-mass has been computed and is shown in Fig. 8. The average laboratory momentum of N is then

$$\langle p_N^{\parallel} \rangle \simeq (p_L^B / m_B) \, M_N \left(1 + \langle p_N^* / M_N \rangle^2 \right)^{1/2} . \qquad (3.29)$$

We now assume that B (m_B = 5.27 GeV) is produced with the same average laboratory momentum as D, p_L^B = 67 GeV. The average momemtum of N then ranges from about 20 to 30 GeV for the masses of interest to us.

The dashed-dotted and dashed lines in Fig. 11a indicate the excluded regions for $\sigma(B) + \sigma(\bar{B}) = 10^{-31}$ cm^2 and 10^{-32} cm^2, respectively. A smaller range of $|U|^2$ is excluded than in the $D \rightarrow Ne$ analysis, except for N masses beyond the $D \rightarrow Ne$ kinematic limit (if $\sigma = 10^{-31}$ cm^2). Even here, the limits are poor because many potential neutral lepton decays occur before the detector.

The decay $B \rightarrow$ (charm) $N\tau$ is also kinematically allowed. We show in Fig. 11b the limits on $|U|^2$ and M_N obtained by analyzing this experiment in terms of such a decay. A small but hitherto unexplored region is excluded.

An "ideal dump" experiment may be imagined with all other parameters the same as in the CHARM experiment, except ℓ_1 reduced to 50m, geometric acceptance ϵ_Ω increased to 10%, and beam momentum doubled (to 800 GeV/c). Other average momenta (of D's, B's, and N's) also are assumed doubled. The ranges of $|U|^2$ and M_N that can be excluded in such an experiment are shown in Fig. 12. Useful limits can be obtained up to $M_N = 2\frac{1}{2}$ to 3 GeV for values of $|U|^2$ down to about 10^{-6}. There will still be an interesting region of larger $|U|^2$ which must be excluded by other means, however.

5. Brief discussion of other beam dump experiments.

We have dwelt on the CHARM experiment as the most recent and statistically powerful of those listed in Table 3. However, others may be able to fill in some of the regions in Fig. 11 not covered by the CHARM experiment. The crucial ingredients are a short path length ℓ_i between the target and the beginning of the decay region, and large geometric acceptance. Thus, because of its short initial decay length ℓ_i, even the relatively low-statistics experiment of Ref. 43 may be able to provide useful information in the range $|U|^2 \sim 10^{-2}$, M_N up to ~ 1.8 GeV. The experiment of Ref. 45, with a very long observed decay length Δ and an initial path length ℓ_i less than half that in the CHARM experiment, also may be able to fill in some gaps. So may the experiment of Ref. 46, with $\ell_i = 56$ m.

D. High-statistics neutrino experiments.

Neutrino beams can produce heavy leptons via the neutral weak current. The production probability is just that of an ordinary weak current times the square of the mixing parameter $|U|^2$ (times a threshold factor).

In a high-statistics neutrino experiment one might expect several million neutral-current events. An upper limit of several distinctive heavy lepton signatures would then correspond to a $|U|^2$ limit of 10^{-6} up to masses where threshold effects become important. At $|U|^2 = 10^{-6}$, the expected lifetimes range from $\sim 10^{-5}$s (at $M_N = 1$ GeV) down to very small values (10^{-13}s at $M_N = 30$ GeV), as illustrated in Fig. 5 for N_μ. If $|U|^2$ is larger, lifetimes can be even shorter. Thus one must be ready for all possibilities noted in Table 2: decays too short

to observe, observable within the detector, or occurring beyond the detector.

1. Decay path too short to observe. One must infer heavy lepton production from unusual event signatures. In the class of models considered here, the decay of the heavy lepton always gives rise to a "right-sign lepton": either a charged lepton or a neutrino. Additional leptons often are present, however. These will be harder on the average than leptons from the decays of hadrons produced at the hadronic vertex. In the models of Ref. 3, N, by virtue of being a Majorana particle, decays equally to leptons of either sign. [50]

The study of dimuons in neutrino events has a long history. The earliest dimuon events were recognized as a sign of charmed particle production. Indeed, most if not all of them appear to be due to charm. This source of dimuons is analyzed exhaustively in a recent high-statistics study, [51] containing reference to earlier work. What is not quoted in Ref. 51 is an upper limit on the number of dimuons that could be due to decays of heavy leptons.

The distributions in azimuthal angle ϕ between μ^+ and μ^- for ν and $\bar{\nu}$ events should be peaked at 180° for charm production. We estimate by eye, taking the Monte Carlo calculations of Ref. 51 at face value, that no more than 10% of ν dimuon events and 7% of $\bar{\nu}$ dimuon events could be associated with a flat ϕ distribution, and hence could come from other sources. This, however, does not provide a particularly stringent bound. Since $\sigma(\mu^-\mu^+)/\sigma(\mu^-) \simeq 0.6\%$ for neutrinos and $\sigma(\mu^-\mu^+)/\sigma(\mu^+) \simeq 0.6\%$ for antineutrinos, and since $\sigma(NC)/\sigma(CC) \simeq 0.3$ for neutrinos and 0.4 for antineutrinos, we estimate

$$\sigma(\text{heavy lepton})\, B(\text{lepton} \to \mu^+\mu^- + \cdots)\ /\ \sigma(NC)$$

$$\lesssim \begin{cases} (0.6\%)(10\%)/0.3 = 2 \times 10^{-3} \quad (\nu) & (3.30) \\ (0.6\%)(7\%)/0.4 = 10^{-3} \quad (\bar{\nu}) & (3.31) \end{cases}$$

Since we estimate (for a lepton mixing with ν_μ) B(lepton $\to \mu^+\mu^- + \ldots$) $\approx$ 8% , the antineutrino limit can only set a restriction of $|U|^2 \lesssim 10^{-2}$, which we anticipated anyhow on the basis of universality. Nonetheless it is reasuring to see that such a limit can be obtained independently. A more precise analysis may be able to strengthen the bounds somewhat.

The production of neutral heavy leptons in neutrino interactions is subject to threshold suppression. For neutrinos on quarks of left-handed or right-handed helicity, the suppression factors for production of massive states are, respectively,

$$\left.\frac{d^2\sigma}{dx\,dy}\right|_{M_N\neq 0} \Big/ \left.\frac{d^2\sigma}{dx\,dy}\right|_{M_N=0}$$

$$= (1 - M_N^2/xs)^2 \qquad \text{(l.h. quarks)} \qquad (3.32)$$

$$= (1 - M_N^2/xs)^2 \left(1 - y - \frac{M_N^2}{xs}\right) \Big/ (1-y) \qquad \text{(r.h. quarks)} \qquad (3.33)$$

where s is the square of the c.m. energy, $s = m_p^2 + 2m_pE_\nu^{lab}$. We may estimate the effect crudely by assuming that only left-handed valence quarks contribute to N production. (Their contribution indeed is the dominant one.) We assume an average structure function

$$x\,q(x) \sim x^{1/2}(1-x)^4 \qquad (3.34)$$

The threshold factor is then

$$\frac{\sigma}{\sigma_0} \equiv \frac{\sigma(E_\nu^{lab}, M_N)}{\sigma(E_\nu^{lab}, 0)} = \frac{f(\tau)}{f(0)} \qquad (3.35)$$

where $\tau \equiv M_N^2/s$, and

$$f(\tau) \equiv \int_\tau^1 dx \left(1 - \frac{\tau}{x}\right)^2 x^{1/2}(1-x)^4 \; . \qquad (3.36)$$

The result is plotted in Fig. 13. Neutrino experiments at present energies are not very efficient in producing heavy leptons much above 5 GeV in mass.

One phenomenon in neutrino interactions for which standard models are unable to account is the observation by several groups of same-sign dileptons. [52,53] In Ref. 9 we discussed one possibility for producing these with the help of a neutral heavy lepton, via

$$\nu + (\text{hadron}) \to \mu^- F^+ + \cdots \qquad (3.37)$$
$$\hookrightarrow N\mu^+$$
$$\hookrightarrow \mu^- + \cdots$$

as part of a multilepton event. Another possibility would involve the sequential decay of one heavy lepton to another, e.g., via

$$\nu + (\text{hadron}) \to N_1 + \cdots \qquad (3.38)$$
$$\hookrightarrow \ell_1 N_2 \bar{\ell}_2$$
$$\hookrightarrow \ell'^+ \ell'^- + \cdots \; .$$

This decay of N_1 could dominate if a right-handed W were sufficiently light, as mentioned in Sec. II.

2. Decay observed within detector. Suppose the detector has length ℓ, and the proper path length for the lepton's decay is L. Then, given a uniform longitudinal distribution of production points within the detector, the probability that the decay distribution is also observed within the detector is

$$P_{p,d} = 1 - \frac{L}{\ell}\left(1 - e^{-\ell/L}\right)$$

$$= \begin{cases} \ell/2L & (\ell \ll L) \\ 1 & (\ell \gg L) \end{cases} \; . \qquad (3.39)$$

The production probability is proportional to $|U|^2$. Thus a measure of efficiency in detecting a decay within a given detector is the function

$$G(|U|^2) \equiv |U|^2 P_{p,d} = |U|^2 \left[1 - \frac{L}{\ell}\left(1 - e^{-\ell/L}\right)\right] , \qquad (3.40)$$

which behaves as $|U|^2$ for large M_N (small L) and $|U|^2\ell/(2L) \sim |U|^4$ for small M_N (large L). Contours of equal $G(|U|^2)$ for $\ell = 10$ m, $p_N = 50$ GeV, are plotted in Fig. 14. Such an experiment sensitive at the $|U|^2 = 10^{-6}$ level for high M_N will only be sensitive at the $|U|^2 = 10^{-4}$ level for $M_N = 1$ GeV.

Searches for secondary vertices are particularly simple in bubble chamber experiments, and have been performed. [54] (We thank J. Lys for discussions on this point.) The total event sample in such experiments makes it unlikely that limits of better than $|U|^2 \lesssim 10^{-4}$ will be set, however.

As an example of the limitations one might encounter in a practical high-statistics neutrino detector, let us imagine a detector of length ℓ to be sensitive to decays taking place at least ℓ_1 from the primary vertex. Then the sensitivity of the experiment depends on

$$|U|^2 P_{p,d} = |U|^2 \left[e^{-\ell_1/L}\left(1 - \frac{\ell_1}{\ell}\right) - \frac{L}{\ell}\left(e^{-\ell_1/L} - e^{-\ell/L}\right) \right] \quad (3.41)$$

(which reduces to (3.40) when $\ell_1 = 0$). In Fig. 15 we plot contours of this quantity times the threshold factor $f(\tau)/f(0)$ defined in Eq. (3.36), for a nominal neutrino energy $E_\nu = 100$ GeV, with $\ell_1 = 10$ cm, $\ell = 10$ m, $p_N = 50$ GeV. The contours of $|U|^2 P_{p,d} f(\tau)/f(0) = (10^{-4}, 10^{-6})$ are appropriate to experiments in which one neutral lepton candidate is detected in at least $(10^4, 10^6)$ neutral current interactions. The corresponding highest neutral lepton masses accessible are about (3,5) GeV.

3. Decay path significantly longer than detector. Neutral current interactions of neutrinos in the shielding upstream of the detector can give rise to decay events in the detector. These will be characterized by a limited total effective mass and a relatively symmetric behavior of any charged leptons with respect to other tracks. If M_N is sufficiently low, it makes sense to try to

reconstruct such possibilities as those listed in Eq. (2.61). Other signatures would be isolated dilepton events with limited total effective mass. A single event of this type has been reported in one experiment, [55] but not confirmed in a larger-statistics sample. [56]

We have assumed throughout most of this discussion that muon neutrinos are the most prevalent. It is conceivable that they can mix with more than one flavor of neutral heavy lepton, as in the model of Ref. 9 . If beams of τ or electron neutrinos can be produced, the neutral heavy leptons they can produce may be different. The relatively weak limits on mixing of ν_τ with other states make this possibility particularly appealing for τ neutrinos.

E. Experiments with incident charged leptons on nucleons

An experiment to search for heavy leptons in the reaction

$$\mu + (\text{nucleon}) \rightarrow (\text{heavy lepton}) + \ldots \quad (3.42)$$

was described in Ref. 57 . Experiments of this type are of considerable interest in searching for weak couplings of right-handed type, but do not set a very stringent limit on left-handed leptons. The reason is very simple: fast muons are produced from K or π 2-body decay and are highly polarized. The μ^+ are mostly left-handed and the μ^- are mostly right-handed. This helicity disfavors weak interactions of V-A type.

The experiment of Ref. 57 can rule out a neutral heavy lepton between 1 and 9 GeV if it is coupled with full strength to the right-handed current. The predicted cross section (times a 10% branching ratio assumed for $\mu\mu\nu$) is equal to the 90% confidence limit experimental upper bound at 1 and 9 GeV, and exceeds it within this range by at most a factor of two, around $M_N \simeq 4$ GeV. The μ^+ beam is $\gtrsim$ 80% left polarized, so $(\mu^+)_R / (\mu^+)_L \lesssim 1/4$. The corresponding cross section for production of N would be bounded by

$$\sigma(\mu^+ + \text{(nucleon)} \to N \text{ (via } \ell\text{.h. current) } + \ldots)$$
$$/\sigma(\mu^+ + \text{(nucleon)} \to N\text{(via full strength r.h. current)} + \ldots)$$
$$< \frac{1}{4}|U|^2 < \begin{cases} 1 & (1\,\text{GeV} \le M_N \le 9\,\text{GeV}) \\ \frac{1}{2} & (M_N \simeq 4\,\text{GeV}) \end{cases} \quad (3.43)$$

so one cannot set a useful bound on $|U|^2$.

Dedicated searches in ep colliders could be a much more powerful source of information about heavy neutral leptons. Both longitudinal polarization states of e will presumably be available. It appears feasible to collect a sample of at least 10^4 $ep \to \nu_e + \ldots$ events in an experiment with $\sqrt{s} \geq 200$ GeV of moderate duration.[58] One could then set bounds of order $|U_{eN}|^2 \lesssim 10^{-4}$ if an experiment were sensitive to N at the single-event level. This would be possible if secondary vertices could be detected. The N is likely to emerge from the collision at a wide angle with at least several tens of GeV of energy (in a typical configuration based on 30 GeV electron and 800 GeV proton energy). Its path length then exceeds a few cm, for $|U|^2 \simeq 10^{-4}$, up to $M_N \simeq$ several GeV. For larger M_N masses one would have to infer the existence of N indirectly.

If a right-handed W exists, it couples to (charged lepton) + N with approximately the same strength that the left-handed W couples to (charged lepton) + ν. The reaction

$$e\,p \to N_e + \cdots \quad (3.44)$$

then can produce N_e with a rate $(M_{WL}/M_{WR})^4$ times that for $ep \to \nu_e X$. If 10^4 events of the latter can be obtained, an experiment observing 1 event of the former would correspond to $M_{W_R} \simeq 10\, M_{W_L} \simeq 800$ GeV. Such a value is not excluded by present direct experiments, [50] though there are indirect suggestions that

$M_{W_R} \gtrsim$ 1-2 TeV, [28] and there is some difference of opinion as to whether this low a value is plausible in grand unification schemes. [59]

F. Production through b decays in e^+e^- annihilations.

Electron-positron annihilations provide copious sources of b quarks at the Υ''' and at higher energies in the continuum. As an example of what can be learned about neutral heavy leptons from the decays of b quarks, let us consider an actual situation based on the CLEO detector at the Cornell Electron Storage Rings (CESR). [60]

The total sample of $B + \bar{B}$ at the $\Upsilon'''(4S)$ is 8.4×10^4. [61] The semileptonic branching ratio $B(B \to (\text{charm})\ell\bar{N})$ is estimated to be $\geq 3 \times 10^{-2}|U|^2$ for $M_N \lesssim 1.8$ GeV. At this mass we estimate that

$$B(N \to \ell^\pm + 3 \text{ prongs}) \simeq 11\,\% \quad (3.45)$$

by analogy with τ decays. [62,63] Then, taking into account of a further track detection efficiency factor, we expect to be able to observe about 250 $|U|^2 P_d$ heavy leptons decaying in the easily observed $\ell^\pm$+(3 charged particle) mode, where P_d is the probability that the decay occurs in the detector. We assume this figure independent of N mass, taking the change in B semileptonic branching ratio to be compensated by a change in the $\ell^\pm$+ 3 prong ratio (3.45). (The $\ell^\pm$+ 3 prong signal may be very weak below $M_N \simeq 1$ GeV, however, if the mass distribution of charged pions in multi-prong τ decays is any guide. [63])

The minimum and maximum decay distances are taken to be $\ell_1 = 3$ mm and $\ell_1 + \Delta = 8$ cm. (Decays outside the beam pipe are harder to observe). The proper path length is approximately

$$L = (p_N/M_N)(1.3\text{ mm})(M_N/1\,\text{GeV})^{-5}\ |U|^{-2}, \quad (3.46)$$

for N in the mass range of interest. We estimate $\langle p_N/M_N \rangle$ from Fig. 8 since the

B's are nearly at rest. Demanding (if no events are seen)

$$250\ |U|^2 P_d \quad < \ 2.3 \qquad (90\%\ c.\ell.) \tag{3.47}$$

we find the contour shown in Fig. 16. Values of $|U|^2$ above about 10^{-2} could be excluded by a search based on present data. Some improvement at the lowest masses (~1 GeV) would follow from extension of Δ. An increase in statistics would lead to a decrease in the upper limit on $|U|^2$ (the lower branch of the curve), particularly for the largest masses, for which the $|U|^2$ upper bound is inversely proportional to the number of B's produced. This search fills in the large $|U|^2$ region to which beam dump experiments are insensitive (Figs. 11, 12).

G. Production through W and Z decays.

The decays $W \to \ell + \bar{N}$ or $Z \to \nu + \bar{N}$ can proceed via mixing of N with the light neutrinos in the class of models considered here. The rates for these processes then will contain a factor of $|U|^2$ in comparison with the rates $W \to \ell + \nu$ (branching ratio $\simeq 8\%$) or $Z \to \nu + \bar{\nu}$ (branching ratio $\simeq 6\%$). Both $Z \to \nu + \bar{N}$ and $Z \to N + \bar{\nu}$ are allowed. Thus we expect

$$B(W \to \ell + \bar{N}) \simeq 0.08\,|U|^2 \left(1 - \frac{M_N^2}{M_W^2}\right)^2 \left(1 + \frac{M_N^2}{2M_W^2}\right), \tag{3.48}$$

$$B(Z \to \nu + \bar{N} \text{ or } \bar{\nu} + N) \simeq 0.12\,|U|^2 \left(1 - \frac{M_N^2}{M_Z^2}\right)^2 \left(1 + \frac{M_N^2}{2M_Z^2}\right), \tag{3.49}$$

when the last factors account for kinematic suppression.

In a large $\bar{p}p$ colliding beam experiment one can envision observing up to about 10^4 W decays to $e^{\pm}\nu$. Thus one expects to be able to probe values of $|U|^2$ down to about 10^{-4} up to N masses which are a substantial fraction of M_W. Eventually e^+e^- collisions at $\sqrt{s} = M_Z$ can lead to samples of at least 10^6 total Z's. This ought to permit the $|U|^2$ limit to be pushed down at least an order of magnitude further. The decays $W \to \ell N$, $Z \to \nu \bar{N}$ or $\bar{\nu} N$ should be quite spectacular. They would lead to unbalanced jets. For very light N ($M_N \lesssim 6$ GeV) and small $|U|^2 \lesssim 10^{-4}$, the N can decay on the average more than 1 cm from its production point.

H. Production through decays of heavy gauge bosons.

A strong reason for considering the neutral heavy lepton is that it is a natural consequence of grand unified theories in which all known fermions belong to a single representation of the symmetry group. In SU(5), this is not the case, [1] but in the simplest model containing SU(5), namely SO(10), the fermions belong to a single 16-plet. [2] Members of this multiplet carry a distinct charge χ depending on their SU(5) content:

$$\begin{array}{lll} 5^* : & \chi = 3 & (\bar{d}, e^-, \nu_e)_L \\ 10 : & \chi = -1 & (\bar{u}, u, d, e^+)_L \\ 1 : & \chi = -5 & (\bar{N})_L \end{array} \tag{3.50}$$

While the unmixed neutral lepton $\bar{N}$ has no electroweak charge, it does have $\chi \neq 0$. The gauge boson coupling to χ (belonging to SO(10)/SU(5)) need only be heavier than about 200-300 GeV, depending on the Higgs structure assumed. [64] Let us call this gauge boson Z_2.

Once the Z_2 has actually been produced, its decay to $N\bar{N}$ occurs with branching ratio $5^2/[5^2 + 5(3^2) + 10(1^2)] \simeq 0.3$ per generation. Even if only one of the three $N\bar{N}$ channels is open, one expects a spectacular Z_2 decay signature 10% of the time.

Another source of N can be a right-handed W, which also arises naturally in SO(10). [50] Indeed, we expect

$$B(W_R \to \ell N) = B(W_L \to \ell \nu) \simeq 1/12 . \tag{3.51}$$

We have estimated the production of W_R and Z_2 at multi-TeV pp and $\bar{p}p$ colliding-beam machines. The hadron structure functions assumed are taken from a forthcoming review of the physics possibilities of such machines. [65] The W_R couplings are estimated by assuming $g_R = g_L$, while the Z_2 couplings are estimated as in Ref. 66 but with Z_0-Z_2 mixing ignored. (The $U(1)_\chi$ coupling is assumed to have the same strength as $U(1)_{Y_W}$, corresponding to case (A.1) of Ref. 66.) The results are shown in Fig. 17. For a pp experiment at $E_{c.m.} = 40$ TeV, sensitive at the $\sigma B = 10^{-39}$ cm^2 level, one can envision production of W_R up to more than 8 TeV, and hence of N up to nearly this mass if a suitable W_R were to exist. The Z_2 is harder to produce than the W_R and, in fact, also harder to produce than a massive boson coupling like the Z_0 of the standard model. First, its couplings to u quarks of both helicities are proportional to the small charge $|\chi| = 1$ (as seen in Eq. (3.50)). When Z_2 does not mix with Z_0 ($M(Z_2) >> M(Z_0)$), *one expects* $\Gamma(Z_2 \to d\bar{d}) = 5\Gamma(Z_2 \to u\bar{u})$. *Since u quarks can be estimated to account* for over 3/4 of Z_0 production at the SPS, this is a notable handicap for Z_2 production. Second, the $U(1)_\chi$ coupling is estimated to be quite weak in grand unified theories, [66] $g_\chi^2/4\pi \leq 1/60$ (to be compared with $g_2^2/4\pi = 1/30$ for weak SU(2)).

IV. CONCLUSIONS AND DISCUSSION

We have presented a variety of experimental tests for neutral heavy leptons mixing weakly with ordinary neutrinos. The most promising of these for low lepton masses involve extension of previously obtained beam dump limits. [47,48] It seems possible with ideal experiments to exclude mixings above $|U|^2 \approx 10^{-5}$-10^{-6} and masses below about 3 GeV. Searches in high-statistics neutrino experiments are capable of pushing to higher masses if short tracks can be detected, or if a clear-cut neutral lepton signature is obtained via reconstruction of lepton-hadron effective masses. New neutral leptons also can be produced in ep interactions and in e^+e^- annhilations to heavy quarks such as b and t. The most promising techniques for higher-mass leptons, however, involve decays of W's and Z's. If they exist at low enough mass, any further gauge bosons that might exist, such as the right-handed W or additional Z's, also are quite likely to produce new leptons in their decays.

We have concentrated on direct searches for new neutral heavy leptons, omitting some very interesting indirect tests. *Foremost among these is the study* of neutrinoless double-beta decay. [6,67]

Others involve searches for rare processes such as $\mu \to e\gamma$. The later paper of Ref. 6 contains a good discussion of several of these tests.

We have bypassed the interesting possibility that, while astrophysical arguments permit only a few flavors of neutrinos (probably $\lesssim 4$) to be light, [68,69] heavier isodoublets are permitted. *They are even allowed to be stable* if their mass exceeds about 2 GeV. [69,70] The decays of Z's into pairs of such objects is an excellent way to search for them. [71] Sequential charged and neutral leptons (weak isodoublets) also may show up prominently in W decays. [72]

The importance of discovering the right-handed partner of the neutrino cannot be overemphasized. At the same time, however, we do not have at present much of a guarantee that this particle exists at any specific mass below 10^{15} GeV. Present limits lie around 1 GeV. The chance that these limits can be extended to 10^4 in the next ten or twenty years at least covers part of this distance (less discouraging if we view it on a logarithmic scale!) The companion effort to push down limits on (light) neutrino mass is, of course, very closely related to this question, and is receiving vigorous experimental attention at present.

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REFERENCES

1. Howard Georgi and S. L. Glashow, Phys. Rev. Lett. 32, 438 (1974).

2. Howard Georgi, in Particles and Fields - 1974, Proceedings of the Meeting of the APS Division of Particles and Fields, Williamsburg, Virginia, edited by C. E. Carlson (AIP, New York, 1975), p. 575; H. Fritzsch and P. Minkowski, Ann. Phys. N.Y., 93, 193 (1975).

3. M. Gell-Mann, P. Ramond, and R. Slansky, in Supergravity, edited by D. Z. Freedman and P. van Nieuwenhuizen (North-Holland, Amsterdam, 1979), p. 315; T. Yanagida, in Proceedings of the Workshop on Unified Theory and Baryon Number in the Universe, edited by O. Sawada and A. Sugamoto (KEK, Tsukuba, Japan, 1979); Rabindra N. Mohapatra and Goran Senjanovic, Phys. Rev. Lett. 44, 912 (1980); Phys. Rev. D23, 165 (1981).

4. H. B. Thacker and J. J. Sakurai, Phys. Lett. 36B, 103 (1971); Y. S. Tsai, Phys. Rev. D4, 2821 (1971); J. D. Bjorken and C. H. Llewellyn Smith, Phys. Rev. D7, 887 (1973): A. Soni, Phys. Rev. D11, 624 (1975); C. H. Albright and C. Jarlskog, Nucl. Phys. B84, 467 (1975); C. Albright, C. Jarlskog, and L. Wolfenstein, ibid. B84, 493 (1975); C. Albright, C. Jarlskog, and M. O. Tjia, ibid. B86, 535 (1975).

5. An extensive list of further theoretical references may be found in Ref. 11 of C. N. Leung and Jonathan L. Rosner, Phys. Rev. D28, 2205 (1983). Many of these works also contain phenomenological analyses. For recent searches see W. Bartel et al., Phys. Lett. 123B, 353 (1983); F. Bergsma et al., Phys. Lett. 128B, 361 (1983); Klaus Winter, rapporteur talk at 1983 International Symposium on Lepton and Photon Interactions at High Energies, Cornell University, August 4-9, 1983, CERN report CERN-EP/83-167, 1983 (unpublished). Suggestions for observing heavy isodoublet neutrinos have recently been made by R. Thun,

Univ. of Michigan report UM HE 83-21, Nov., 1983, submitted to Phys. Lett. B, and R. Shrock, in Proceedings of the 1982 DPF Summer Study on Elementary Particle Physics and Future Facilities, Snowmass, Colo., edited by Rene Donaldson, Richard Gustafson, and Frank Paige, Fermi National Accelerator Laboratory, 1982, p. 261. For a broad range of topics on neutrino masses, see also R. Shrock, 1982 Snowmass proceedings, pp. 259, 264, 291.

6. Mohapatra and Senjanovic, Ref. 3.

7. D. Wyler and L. Wolfenstein, Nucl. Phys. B218, 205 (1983).

8. C. N. Leung and S. T. Petcov, Phys. Lett. 125B, 461 (1983).

9. Leung and Rosner, Ref. 5.

10. Robert E. Shrock, Phys. Lett. 96B, 159 (1980); Phys. Rev. D24, 1232 (1981); in Weak Interactions as Probes of Unification (Virginia Polytechnic Institute - 1980), edited by G. B. Collins, L. N. Chang, and J. R. Ficenec (AIP, New York, 1981), p. 368; in 1982 Snowmass proceedings, op. cit., Ref. 5, p. 291; report presented at Theoretical Symposium on Intense Medium Energy Sources of Strangeness (TSIMESS), Santa Cruz, Calif., March, 1983, State University of New York (Stony Brook) report ITP-SB-83-39 (unpublished): C. Y. Pang et al., Phys. Rev. D8, 1989 (1973); R. Abela et al., Phys. Lett. 105B, 263 (1981); R. S. Hayano et al., Phys. Rev. Lett. 49, 1305 (1982); D. A. Bryman et al., Phys. Rev. Lett. 50, 1546 (1983).

11. M. Gronau, SLAC report SLAC-PUB-2967, Aug., 1982 (unpublished), and Phys. Rev. D28, 2762 (1983); Bergsma et al., Ref. 5; Winter, Ref. 5.

12. A. J. Buras, J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B135, 66 (1978).

13. Particle Data Group, M. Aguilar-Benitez et al., Phys. Lett. 111B, 1 (1982).

14. We regard as preliminary the indications that $m(\bar{\nu}_e) = 33 \pm 2$ eV from one $^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$ experiment. See M. Shaevitz, invited talk at 1983 International Symposium on Lepton and Photon Interactions at High Energies, Cornell University, August 4-9, 1983 (Columbia University report Nevis R#1295, 1983, unpublished).

15. S. S. Gershtein and Ya. B. Zel'dovich, ZhETF Pis' Red. 4, 174 (1966) [Sov. Phys. - JETP Letters 4, 120 (1966)]; G. Marx and A. Szalay, in Neutrino 72, edited by A. Frenkel and G. Marx, Omkdk-Technoinform, Budapest, 1972, v.1, p. 123; R. Cowsik and J. McClelland, Phys. Rev. Lett. 29, 669 (1972); S. Tremaine and J. E. Gunn, Phys. Rev. Lett. 42, 407 (1979); K. Freese and D. N. Schramm, Fermilab preprint 83/46 - THY, May, 1983 (unpublished).

16. M. Gronau and S. Nussinov, Fermilab-Pub-82/52-THY, 1982 (unpublished); M. Gronau and R. Yahalom, Nucl. Phys. B., to be published. See also R. N. Mohapatra, Invited Talk presented at LAMPF II workshop held at Los Alamos, N.M., July 18-29, 1983, Univ. of Maryland Publ. No. 25, 1983 (unpublished).

17. This was considered by Howard Georgi (private communication) in constructing the SO(10) model described in Ref. 2, and more explicitly in First Workshop on Grand Unification (University of New Hampshire, April 1980), edited by Paul H. Frampton, Sheldon L. Glashow, and Asim Yildiz, Math Sci. Press, Brookline, Mass., 1980, p. 297; H. Georgi and D. V. Nanopoulos, Phys. Lett. 82B, 392 (1979); Nucl. Phys. B155, 52 (1979); B159, 16 (1979).

18. C. N. Leung, Ph.D. Thesis, University of Minnesota, 1983 (unpublished).

19. R. Shrock and L. L. Wang, Phys. Rev. Lett. 41, 1692 (1978).

20. John Jaros, SLAC report SLAC-PUB-3248, Oct., 1983 (unpublished); E. Fernandez et al., Phys. Rev. Lett. 51, 1022 (1983).

21. This follows from $\tau_b/\tau_\mu = (m_\mu/m_b)^5\ [2.75\,|V_{bc}|^2]^{-1}$ and the limit $\tau_b > 10^{-12}$ sec. See Refs. 20 and 22.

22. Sheldon Stone, invited talk at 1983 International Symposium on Lepton and Photon Interactions at High Energies, Cornell University, August 4-9, 1983, unpublished.

23. W. Bacino et al., Phys. Rev. Lett. 41, 13 (1978); Ch. Berger et al., Phys. Lett. 99B, 489 (1981); Ref. 13.

24. J. A. Jaros et al., Phys. Rev. Lett. 51, 955 (1983).

25. T. Kinoshita, Phys. Rev. Lett. 2, 477 (1959); S. Berman, ibid. 1, 468 (1958); R. E. Marshak, Riazuddin, and C. P. Ryan, Theory of Weak Interactions in Particle Physics (Wiley-Interscience, New York, 1969); D. Bryman, P. Depommier, and C. Leroy, Phys. Rep. 88, 151 (1982); W. Marciano and A. Sirlin, Phys. Rev. Lett. 36, 1425 (1976); T. Goldman and W. Wilson, Phys. Rev. D15, 709 (1977).

26. D. A. Bryman et al., Phys. Rev. Lett. 50, 7 (1983).

27. J. L. Cortes, X. Y. Pham, and A. Tounsi, Phys. Rev. D25, 188 (1982).

28. G. Beall, M. Bander, and A. Soni, Phys. Rev. Lett. 48, 848 (1982); G. Beall and A. Soni, UCLA report UCLA/83/TEP/8, May, 1983, presented at XVIII Recontre de Moriond, March, 1983; Haim Harari and Miriam Leurer, Fermilab Report FERMILAB-Pub-83/59-THY, July, 1983 (unpublished); F. J. Gilman and M. H. Reno, SLAC report SLAC-PUB-3238, October, 1983 (unpublished).

29. M. Gronau, Ref. 11.

30. J. L. Rosner, Nucl. Phys. B126, 124 (1977).

31. D. Meyer et al., Phys. Lett. 70B, 469 (1977).

32. K. G. Hayes et al., Phys. Rev. D25, 2869 (1982).

33. R. C. Ball et al., UM HE 83-11. A more recent report by R. C. Ball et al., UM HE 83-13, revised 8-2-83, submitted to the 1983 International Symposium on Lepton and Photon Interactions at High Energies, Cornell University, August 4-9, 1983, quotes slightly different x and $p^\perp$ distributions: $E\, d^3\sigma/dp^3 \sim (1-x)^n\, e^{-ap^\perp}$; $n = 3.0 \pm 0.2 \pm 0.4$, $a = 2.7 \pm 0.2 \pm 0.4$. We also understand (B. Roe, private communication) that a two-component x distribution is possible, with both soft and hard components of charm production.

34. F. Halzen, in 21st International Conference on High Energy Physics, Proceedings, Paris, France, July 26-31, 1982, edited by P. Petiau and M. Porneuf, Les Editions de Physique, Les Ulis, France, 1982, p. C3-381.

35. F. Halzen, private communication.

36. S. Reucroft, CERN report CERN/EP 83-155 (unpublished), presented at XIV International Symposium on Multiparticle Dynamics, Lake Tahoe, Calif., 22-27 July, 1983. See especially the experiment by A. Diamant-Berger et al., Phys. Rev. Lett. 44, 507 (1980).

37. J. M. Feller et al., Phys. Rev. Lett. 40, 247 (1978); W. Bacino et al., ibid. 43, 1073 (1979).

38. Carl H. Albright, Robert Shrock, and J. Smith, Phys. Rev. D20, 2177 (1979); E. G. Floratos, Stephan Narison, and Eduardo de Rafael, Nucl. Phys. B155, 115 (1979);Hartmut Krasemann, Phys. Lett. 96B,397 (1980).

39. N. W. Reay, invited talk, 1983 International Symposium on Lepton and Photon Interactions at High Energies, Cornell University, August 4-9, 1983 (unpublished).

40. A. Chen et al., Phys. Rev. Lett. 51, 634 (1983).

41. A. Benvenuti et al., Phys. Rev. Lett. 35, 1486 (1975).

42. H. R. Gustafson et al., Phys. Rev. Lett. 37, 474 (1976).

43. D. J. Bechis et al., Phys. Rev. Lett. 40, 602 (1978).

44. G. Kalbfleisch, submitted to Neutrino '79 Conference, Bergen, Norway (unpublished).

45. R. H. Bernstein et al., Rutgers University report RU-1-83, 1983 (unpublished).

46. Ball et al., second of Refs. 33.

47. F. Bergsma et al., Ref. 5.

48. K. Winter, Ref. 5.

49. A. Bodek et al., Phys. Lett. 113B, 77 (1982); A. Bodek et al., in Neutrino '82, Proceedings of 12th International Neutrino Conference, Balatonfured, Hungary, June 14-19, 1982, edited by A. Frenkel and L. Jenik, Budapest, Hungary, Central Research Institute for Physics, 1982, v. 1, p. 109; J. L. Ritchie et al., Univ. of Rochester report UR-859, July, 1983 (unpublished).

50. Wai-Yee Keung and Goran Senjanovic, Phys. Rev. Lett. 50, 1427 (1983).

51. H. Abramowitz et al., Z. Phys. C15, 19 (1982).

52. M. J. Murtagh, in Proceedings of the 1979 International Symposium on Lepton and Photon Interactions at High Energies, Fermilab, August 23-29, 1979, edited by T. B. W. Kirk and H. D. I. Abarbanel, Fermi National Accelerator Laboratory, Batavia, IL, 1980, p. 277; J. Knobloch, J. Allaby (M. Jonker et al.), Maria Willutzky (A. Haatuft et al.), and T. Y. Ling, in Neutrino '81 (Proceedings of the 1981 International Conference on Neutrino Physics and Astrophysics), Maui, Hawaii, July 1-8, 1981, edited by R. J. Cence, E. Ma, and A. Roberts (High Energy Physics Group, Univ. of Hawaii, Honolulu, 1981), v. 1, p. 421, 429, 442, 449; H. C. Ballagh et al., Phys. Rev. D24, 7 (1981); V. V. Ammosov

et al., Phys. Lett. 106B, 151 (1981); A. Haatuft et al., Nucl. Phys. B222, 365 (1983).

53. For one recent theoretical analysis, see J. Smith and G. Valenzuela, Phys. Rev. D28, 1071 (1983).

54. J. Lys, private communication.

55. G. G. Volkov et al., Yad. Fiz. 27, 1608 (1978) [Sov. J. Nucl. Phys. 27, 847 (1978)].

56. C. Baltay, in Proceedings of the 19th Interantional Conference on High Energy Physics, Tokyo, 1978, edited by S. Homma, M. Kawaguchi, and H. Miyazawa (Physical Society of Japan, Tokyo, 1979) p. 882.

57. A. R. Clark et al., Phys. Rev. Lett. 46, 299 (1981).

58. T. A. O'Halloran, Jr., in Proceedings of the 1982 DPF Summer Study of Elementary Particle Physics and Future Facilities, Snowmass, Colo., edited by Rene Donaldson, Richard Gustafson, and Frank Paige, Fermi National Accelerator Laboratory, 1982, p. 82.

59. For one discussion and further references, see Nilendra G. Deshpande and R. J. Johnson, Phys. Rev. D27, 1165 (1983).

60. M. Gronau, N. Horwitz, and J. Rosner, CLEO Internal Note, December, 1983 (unpublished). We thank N. Horwitz for providing details of the detector.

61. S. Behrends et al., Phys. Rev. Lett. 50, 881 (1983); S. Stone, Ref. 22.

62. The $\tau \to \nu_\tau + 3$ charged prong branching ratio is about 15% (see Ref. 63), while the total effective number of channels in τ decay is $\Phi = 5$. Since we expect $\Phi_e \cong 7$ for $M_{N_e} = 1$-2 GeV (see Fig. 3a), the corresponding $N_e \to \ell^-$ + (three charged prongs) branching ratio is expected to be about $(5/7) \cdot (15\%) \cong 11\%$. The difference arises from the additional contribution of neutral currents to N decays.

63. J. A. Jaros et al., Phys. Rev. Lett. 40, 1120 (1978); D. M. Ritson, 1982 Paris Conf., op cit., p. C3-52; G. Trilling, 1982 Paris Conf., op. cit., p. C3-57; H.-J. Behrend, 1982 Paris Conf., op. cit., p. C3-72.

64. Nilendra G. Deshpande and David Iskandar, Phys. Rev. Lett. 42, 20 (1979); Phys. Lett. 87B, 383 (1979); Nucl. Phys. B167, 223 (1980); Nilendra G. Deshpande, in High Energy Physics - 1980 (XX International Conference, Madison, Wisconsin), edited by Loyal Durand and Lee G. Pondrom (AIP, New York, 1981), p. 431, and expanded version in Univ. of Oregon report OITS-141, May, 1980 (unpublished); Richard W. Robinett and Jonathan L. Rosner, Phys. Rev. D25, 3036 (1982); Leung and Rosner, Ref. 9; Leung, Ref. 18. More general extra-Z models have also been discussed by others, including V. Barger, Ernest Ma, and K. Whisnant, Phys. Rev. D26, 2378 (1982), and specifically in the context of SO(10) by V. Barger, E. Ma, K. Whisnant, N. Deshpande, and R. Johnson, Phys. Lett. 118B, 68 (1982).

65. E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, in preparation.

66. Robinett and Rosner, Ref. 64.

67. A. Halprin, P. Minkowski, H. Primakoff, and S. P. Rosen, Phys. Rev. D13, 2567 (1976).

68. G. Steigman, D. N. Schramm, and J. E. Gunn, Phys. Lett. 66B, 202 (1977); Jongmann Yang, David N. Schramm, Gary Steigman, and Robert T. Rood, Astrophys. J. 227, 697 (1979).

69. Michael S. Turner, in Neutrino '81 (Proceedings of the 1981 International Conference on Neutrino Physics and Astrophysics), Maui, Hawaii, July 1-8, 1981, edited by R. J. Cence, E. Ma, and A. Roberts (High Energy Physics Group, Univ. of Hawaii, Honolulu, 1981), v. 1, p. 95.

70. B. W. Lee and S. Weinberg, Phys. Rev. Lett. 39, 165 (1977).

71. R. Thun, Ref. 5; R. Shrock, Ref. 5.

72. D. B. Cline and C. Rubbia, Phys. Lett. 127B, 277 (1983).

TABLE 1. Branching ratios into specific final states for low-mass neutral heavy leptons, in percent

Lepton	N_e			N_μ			N_τ		
M(N)(GeV)	0.5	1	2	0.5	1	2	0.5	1	2
Final State									
$\mu^- e^+ \nu$	11.4	13.2	13.6	13.6	13.8	13.8	0	0	0
$e^- e^+ \nu$	9.0	8.1	7.9	2.4	1.9	1.8	5.8	4.9	4.6
$\mu^- \mu^+ \nu$	0.8	1.5	1.7	5.5	7.3	7.7	2.4	3.9	4.4
$\nu\nu\bar{\nu}$	15.8	14.4	13.9	19.0	15.0	14.1	46.0	38.3	36.2
ℓ^-+had.	47.2	43.0	41.8	40.5	41.2	41.3	0	0	0
ν + had.	15.8	19.9	21.1	18.9	20.8	21.3	45.7	52.9	54.8

TABLE 2. Neutral heavy lepton signatures in neutrino neutral-current events.

Path length from primary vertex	Signatures
Too short to detect	Unusual lepton from primary vertex Unusual lepton energy distribution
Within detector	Secondary vertex containing a lepton
Outside detector	Looks like a neutral-current event. May see decay leptons in detector from upstream interactions.

TABLE 3. Comparison of some experiments capable of setting limits via charm and b production on heavy lepton masses and mixings with light neutrinos.

Experiment	Protons on target	Path length ℓ_i to beginning of decay volume	Length Δ of decay volume
Fermilab, 1975 (Ref. 41)	3.5×10^{17} (300 GeV)	400 m	2 m
Fermilab, 1976 (Ref. 42)	(300 GeV)	590 m	
Fermilab, 1978 (Ref. 43)	2.8×10^{13}	6.2 m	9.2 m
Fermilab, 1979 (Ref. 44)	8×10^{17} (400 GeV)	700 m	
Fermilab (Ref. 45)	2.6×10^{17} (400 GeV)	210 m	235 m
Fermilab, 1983 (Ref. 46)	2.7×10^{17} (400 GeV)	56 m	7.4 m
CERN, 1983 (Refs. 47, 48)	2.4×10^{18} (400 GeV)	480 m	35 m

Figure Captions

Fig. 1. Boundaries of allowed regions of $|U|^2$ (mixing strength) and M_N for heavy neutral leptons in specific models. Lines with $|U|^2 \sim M_N^{-2}$ correspond to allowed ranges of Dirac mass scale μ. (a) Model of Gell-Mann *et al.* and Yanagida (Ref. 3). Lines with $|U|^2 \sim M_N^{-1}$ correspond to experimental upper limits on neutrino masses. (b) Model of Ref. 9. Horizontal lines correspond to bounds based on universality for processes involving ν_μ ($|U|^2 \leq 0.8\%$), and ν_τ ($|U|^2 \leq 10\%$ anticipated.) Vertical lines correspond to bounds on N masses (Eqs. (2.24), (2.25)).

Fig. 2. Typical decays of a neutral heavy lepton via (a) charged current, and (b) neutral current. Here the lepton ℓ_i denotes e, μ, or τ.

Fig. 3. Effective number of channels Φ for decays of neutral leptons, as function of neutral lepton mass M_N. (a) Φ_e: lepton mixed with ν_e. (b) Φ_μ : lepton mixed with ν_μ . (c) Φ_τ : lepton mixed with ν_τ .

Fig. 4. Branching ratios of neutral heavy leptons mixed with ν_e (open circles), ν_μ (solid dots), or ν_τ (crosses). (a) to charged leptons; (b) to neutrinos; (c) to charged lepton + hadrons; (d) to neutrino + hadrons. Irregularities are due to opening of specific channels.

Fig. 5. Contours of fixed lifetime of a neutral heavy lepton mixed with ν_μ (Eq. (2.48)). Predicted lifetimes of leptons mixed with ν_e or ν_τ differ by less than a factor of 2 from these values over the range 1 GeV $\leq M_N \leq$ 50 GeV.

Fig. 6. Kinematic factor $I_1(\frac{m_s}{m_c}, \frac{M_N}{m_c}, \frac{m_\ell}{m_c})$, defined in Eq. (2.40), entering into semileptonic branching ratio $B(D \to [S=-1]\, N\ell^+)$. Solid line: $\ell = e$; dashed line: $\ell = \mu$. We have taken $m_s = 0.15$ GeV, $m_c = 1.5$ GeV. Conventionally one often sees m_c replaced by m_D and m_s by an incoherent sum of m_K and m_{K^*}. For our purposes the results are similar.

Fig. 7. Comparisons of predicted branching ratios for semileptonic and leptonic charmed particle decays to heavy leptons, in units of mixing strength $|U|^2$.

Fig. 8. Kinematic factor $I_1(\frac{m_c}{m_b}, \frac{m_\ell}{m_b}, \frac{M_N}{m_b})$ entering into semileptonic branching ratio $B(B \to [\text{charm}]\ell\bar{N})$ (solid line), and average value of p_N/M_N in B center-of-mass (dashed line).

Fig. 9. Average semileptonic branching ratio of B mesons to neutral heavy leptons N, in units of mixing strength $|U|^2$.

Fig. 10. Limits from leptonic decay of the D quoted in Ref. 48 on a heavy lepton N coupled to e with strength U_{eN}.

Fig. 11. Reanalysis of the experiment described in Refs. 47 and 48.
a) Solid line: $D \to Ne$. Dotted line: D semileptonic decay. Dash-dotted line: B semileptonic decay, $\sigma(B) + \sigma(\bar{B}) = 10^{-31}$ cm^2. Dashed line: B semileptonic decay, $\sigma(B)+\sigma(\bar{B}) = 10^{-32}$ cm^2. b) Similar figure as a), for $B \to (\text{charm})\tau N$. The solid line corresponds to $\sigma(B) + \sigma(\bar{B}) = 10^{-31}$ cm^2, and the dashed to 10^{-32} cm^2.

Fig. 12. "Ideal" beam dump experiment with same parameters as those for Ref. 47, 48 except: $\ell_1 = 50$ m, $\epsilon_\Omega = 0.1$, $p_L = 800$ GeV. Variation of cross sections between 400 and 800 GeV is ignored. Curves as in Fig. 11a.

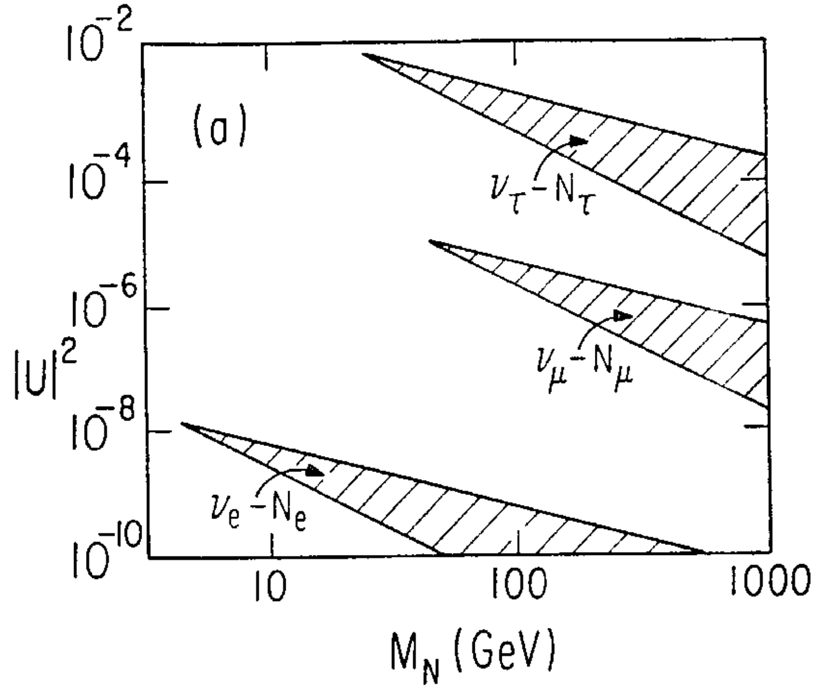
Fig. 13. Threshold factors for production of heavy leptons, as functions of neutrino laboratory energy E_ν. Curves are labeled by M_N in GeV.

Fig. 14. Contours of equal $G(|U|^2) \equiv |U|^2 P_{p,d}$ for detector with $\ell = 10$m, $p_N = 50$ GeV/c. Here we have assumed Eq. (2.48) for the N lifetime. Curves are labeled by values of G.

Fig. 15. Contours of equal $G = |U|^2 P_{p,d} \times$ (threshold factor) for a detector with $\ell_1 = 10$ cm, $\ell = 10$ m, $p_N = 50$ GeV/c. Eq. (2.48) is taken for N lifetime. A neutrino energy of $E_\nu = 100$ GeV is assumed in calculating the threshold factor (3.35).

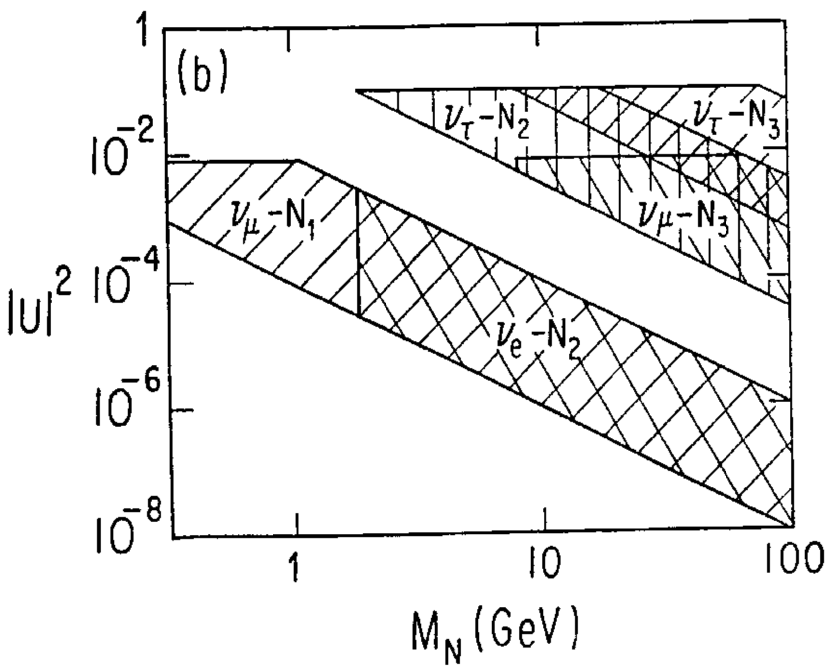
Fig. 16. Limits obtainable on heavy lepton mass and mixing from B production at the $\Upsilon'''(4S)$, based on a sample of 84K $B+\bar{B}$, $\ell_1 = 3$ mm, $\ell_1 + \Delta = 8$ cm, and detection in the (charged lepton) + (3 charged hadron) mode.

Fig. 17. Estimates for production and detection of W_R (a,b) and Z_2(c,d) in pp(a,c) and $\bar{p}$p(b,d) collisions. We show cross sections times branching ratios into specific final states which might be easily detected: eN for W_R, and $\ell^+\ell^-$ for Z_2.



(a)
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$|U|^2$
$\nu_\tau - N_\tau$
$\nu_\mu - N_\mu$
$\nu_e - N_e$
10
100
1000
M_N (GeV)

FIG. 1a



(b)
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$|U|^2$
$\nu_\tau - N_2$
$\nu_\tau - N_3$
$\nu_\mu - N_3$
$\nu_\mu - N_1$
$\nu_e - N_2$
1
10
100
M_N (GeV)

FIG. 1b

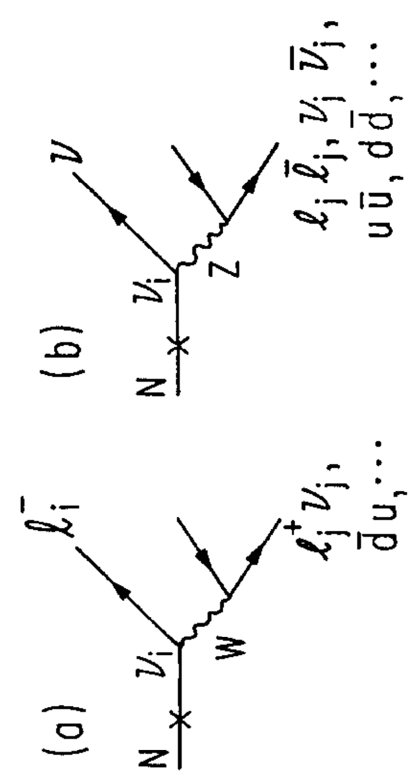


FIG. 2

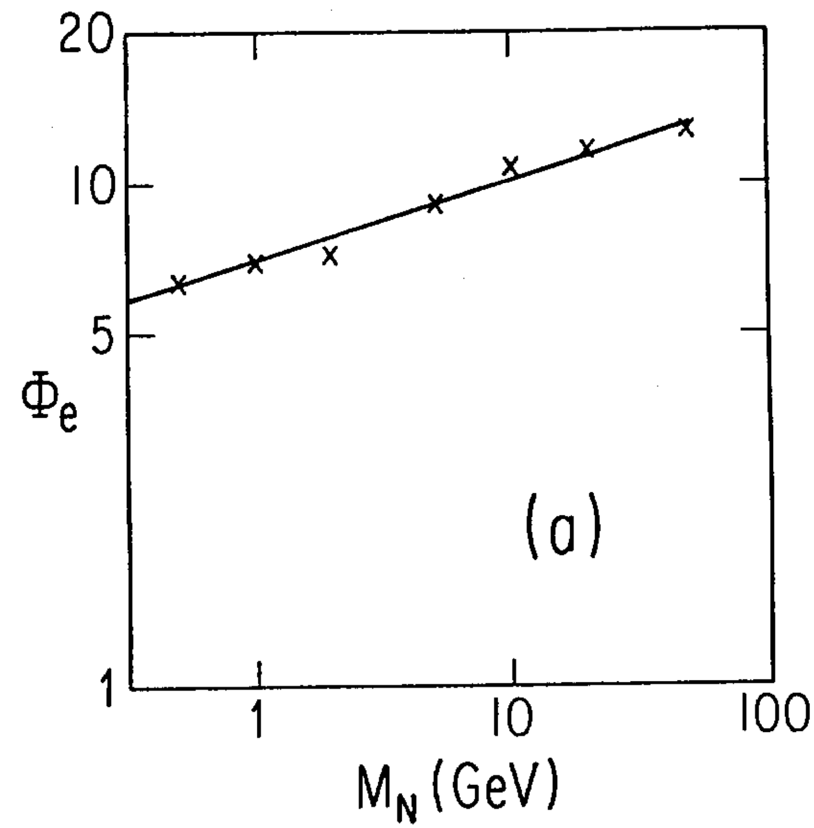


FIG. 3a

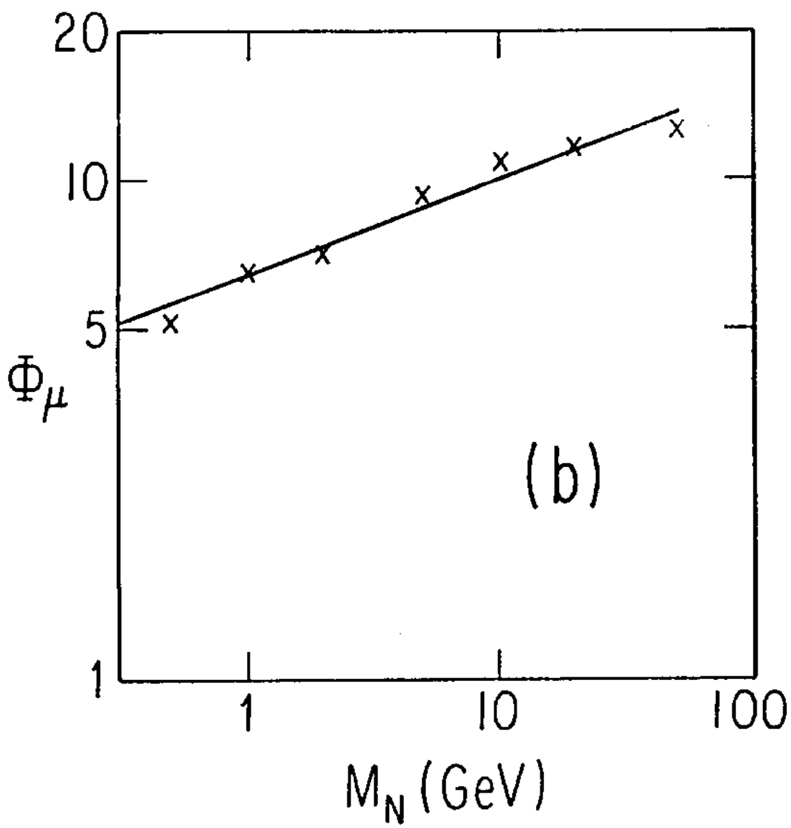


FIG. 3b

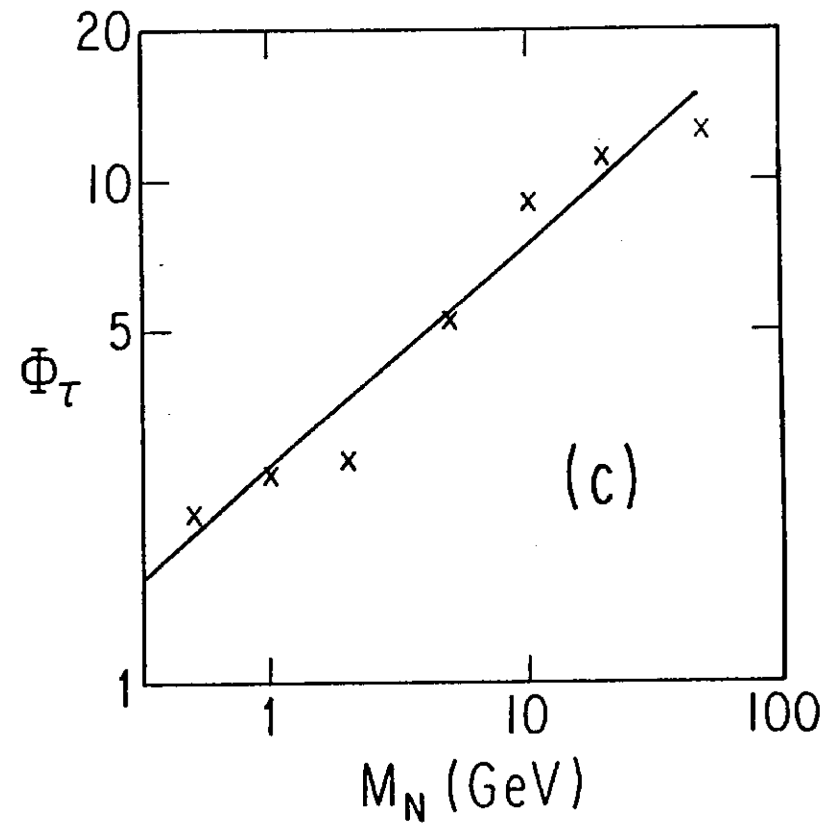
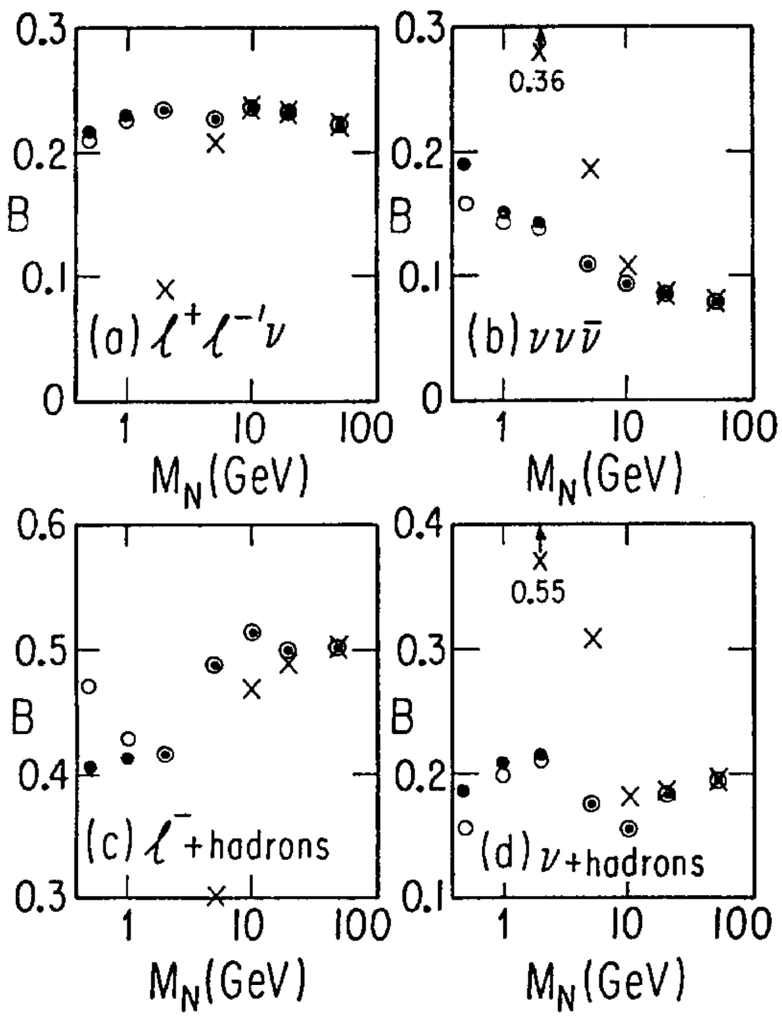
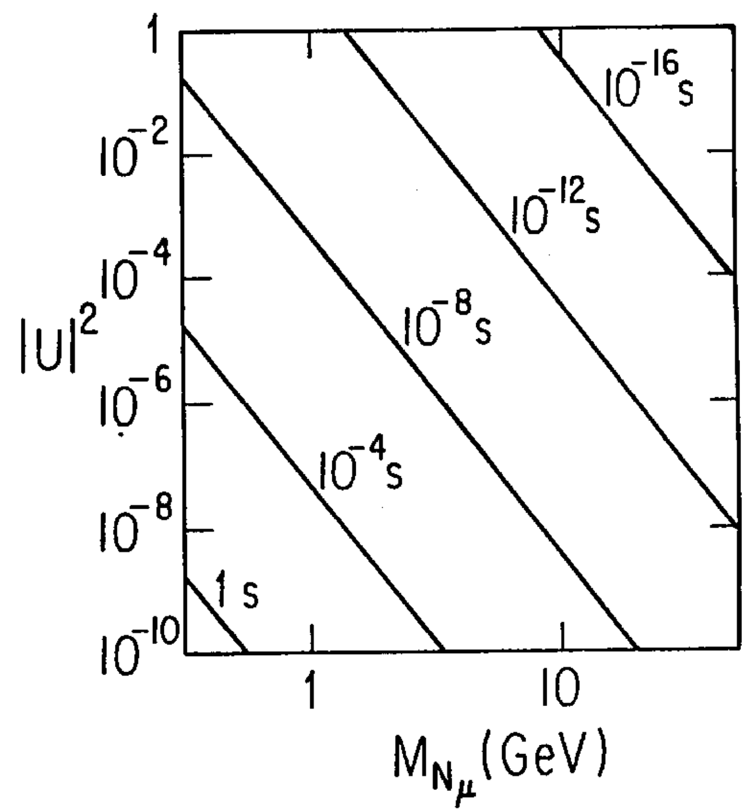


FIG. 3c



0.3
0.2
0.1
0
B
(a) $\ell^+\ell^{-\prime}\nu$
1
10
100
M_N(GeV)
0.36
(b) $\nu\nu\bar{\nu}$
0.6
0.5
0.4
0.3
(c) ℓ^-+hadrons
0.55
(d) ν+hadrons

FIG. 4



1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$|U|^2$
10^{-16}s
10^{-12}s
10^{-8}s
10^{-4}s
1 s
1
10
M_{N_μ}(GeV)

FIG. 5

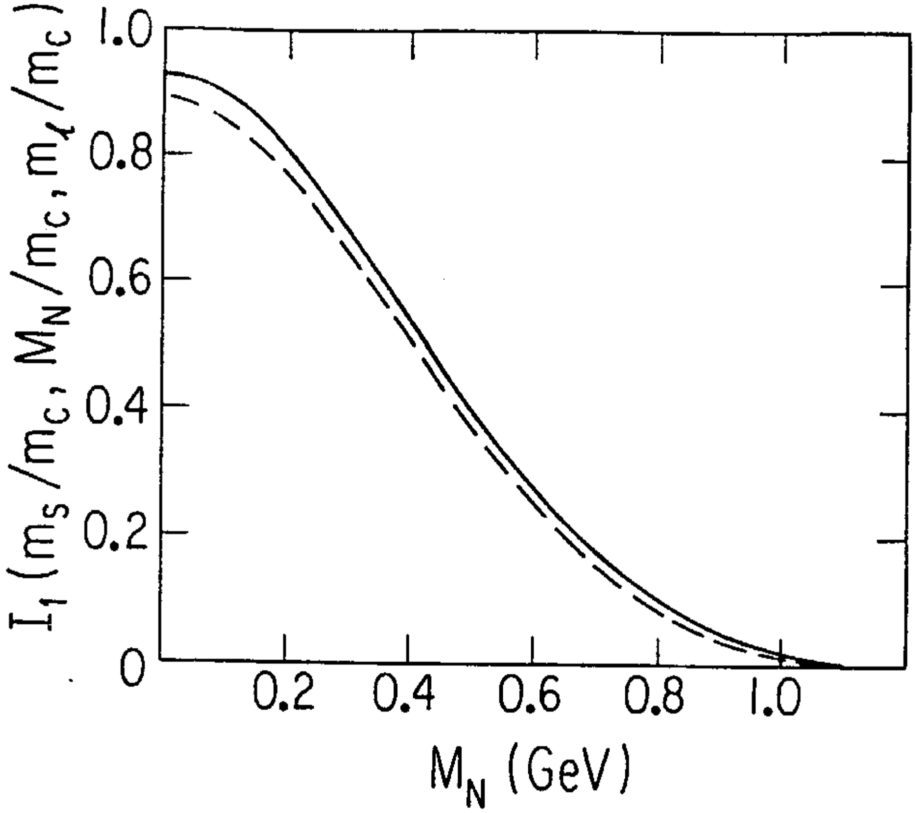

1.0
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
$I_1(m_s/m_c, M_N/m_c, m_\ell/m_c)$
M_N (GeV)

FIG. 6

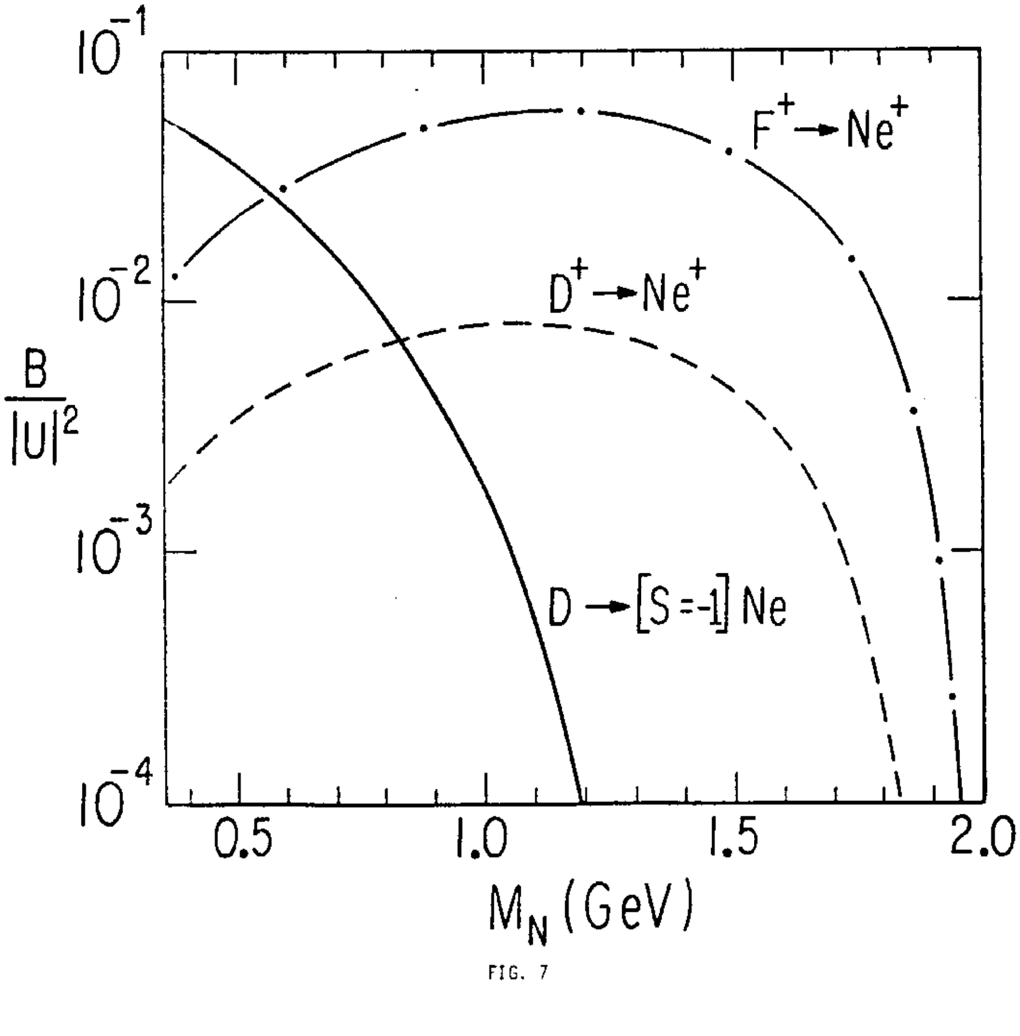

10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\frac{B}{|U|^2}$
0.5
1.0
1.5
2.0
M_N (GeV)
$F^+ \to Ne^+$
$D^+ \to Ne^+$
$D \to [S=-1]\ Ne$

FIG. 7

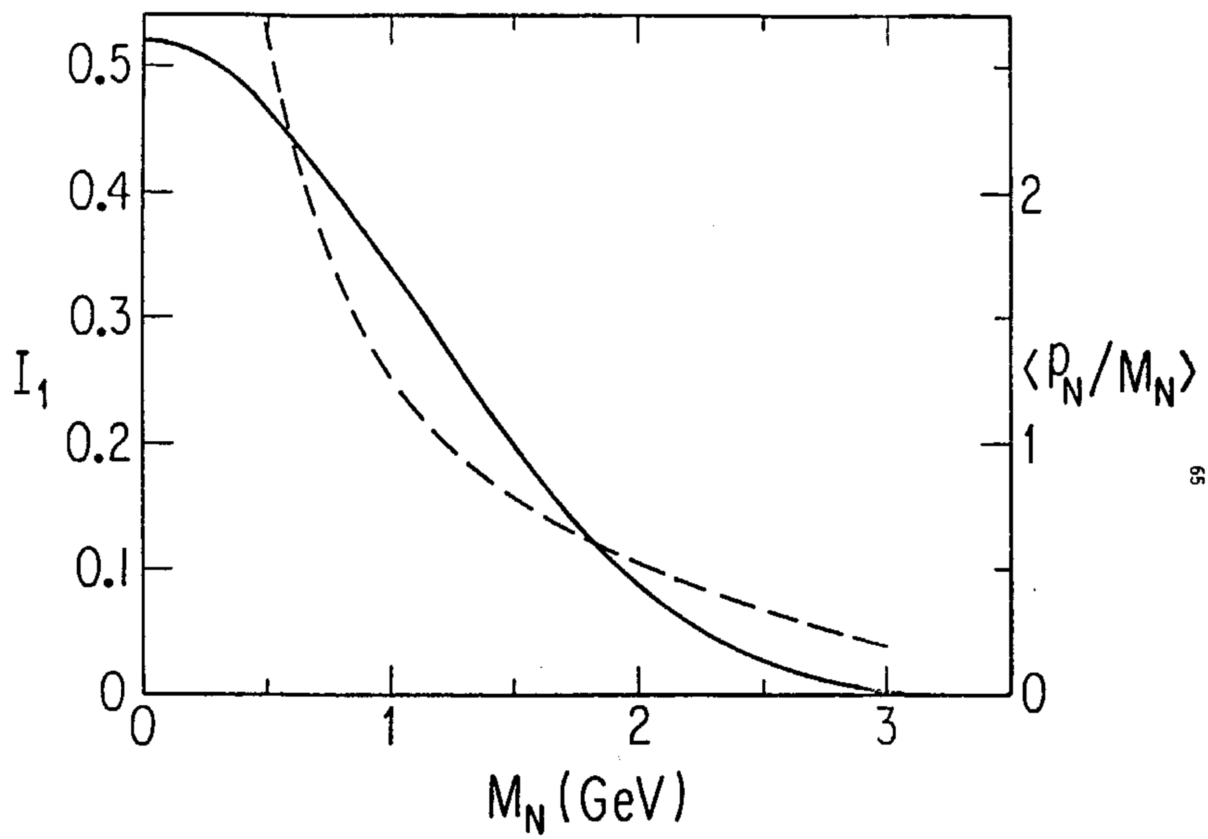

0.5
0.4
0.3
0.2
0.1
0
I_1
0
1
2
3
M_N (GeV)
2
1
0
$\langle p_N/M_N \rangle$

FIG. 8

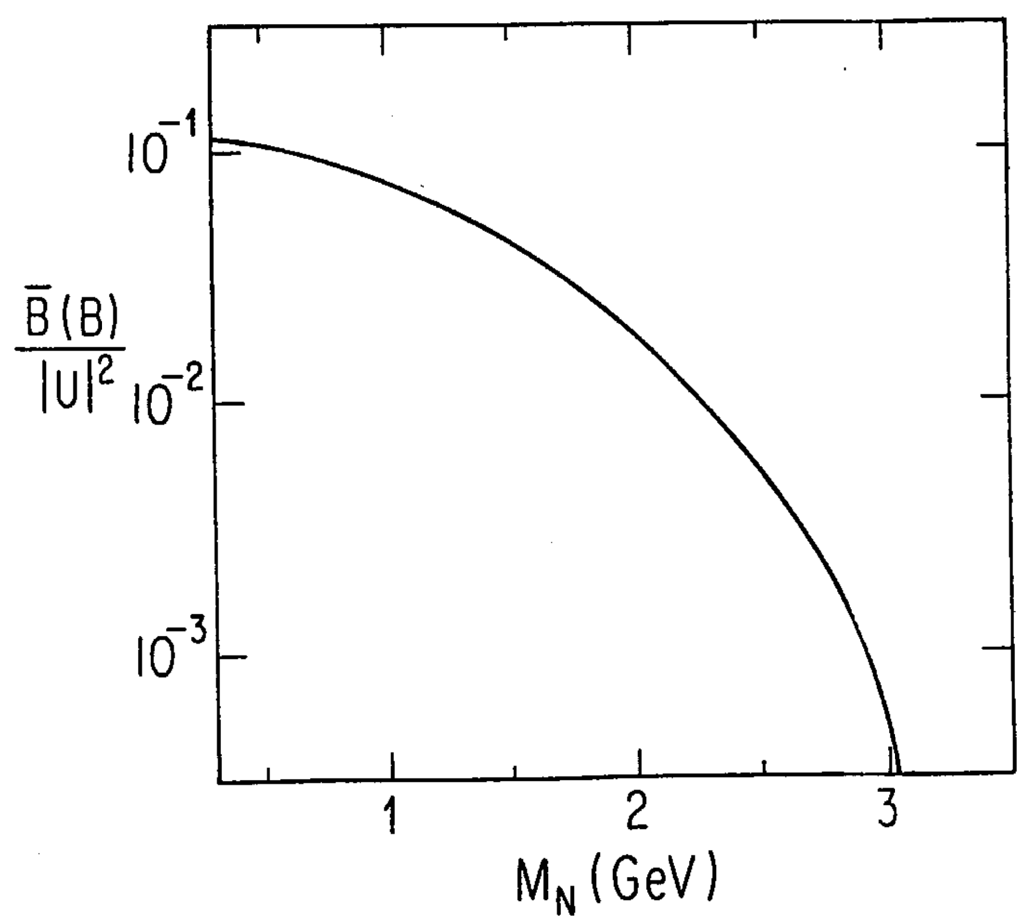

10^{-1}
10^{-2}
10^{-3}
$\frac{\bar{B}(B)}{|U|^2}$
1
2
3
M_N (GeV)

FIG. 9

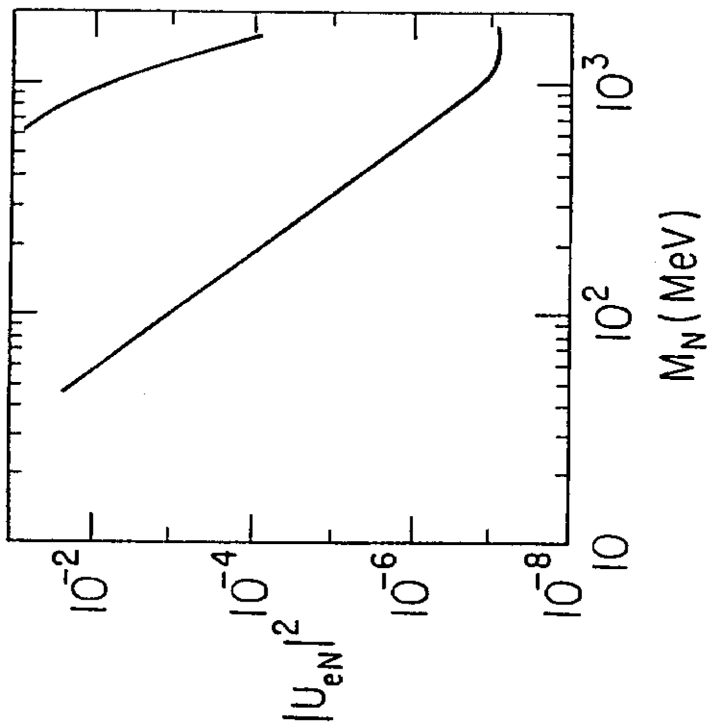


FIG. 10

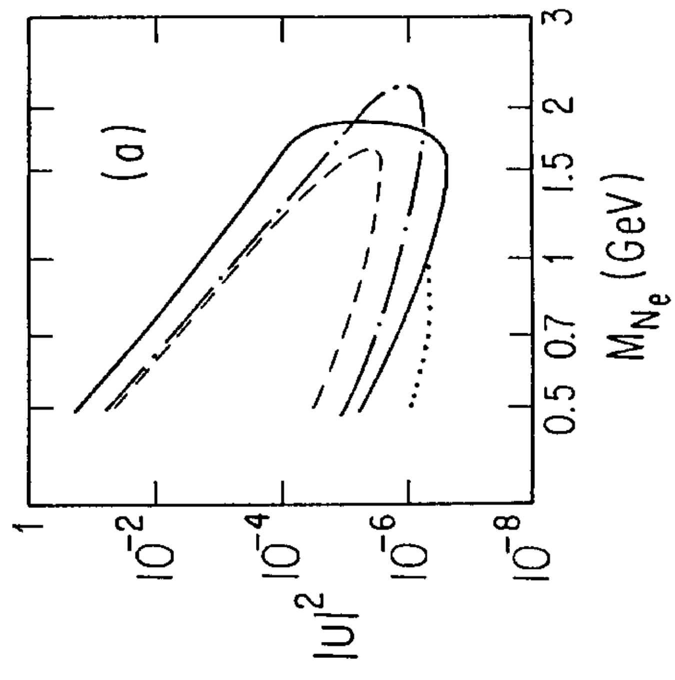


FIG. 11a

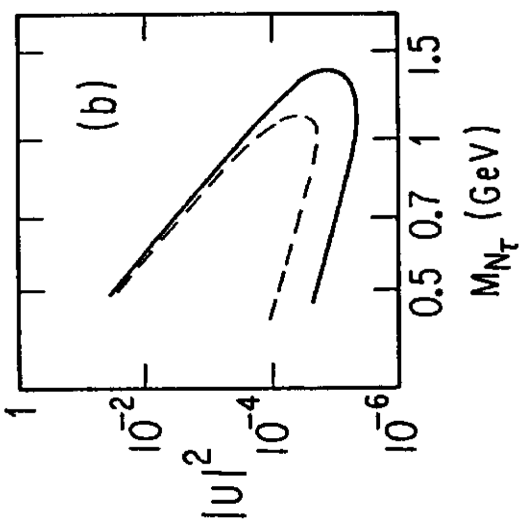


FIG. 11b

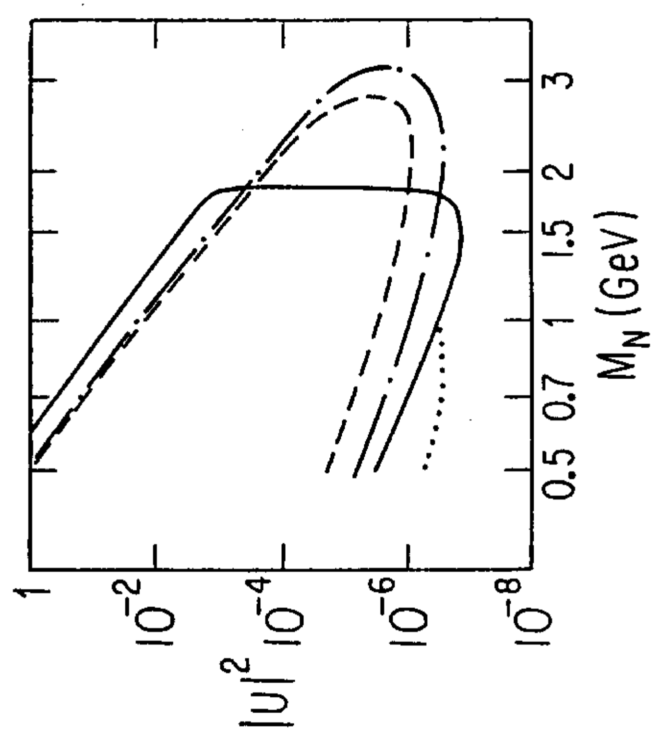


FIG. 12

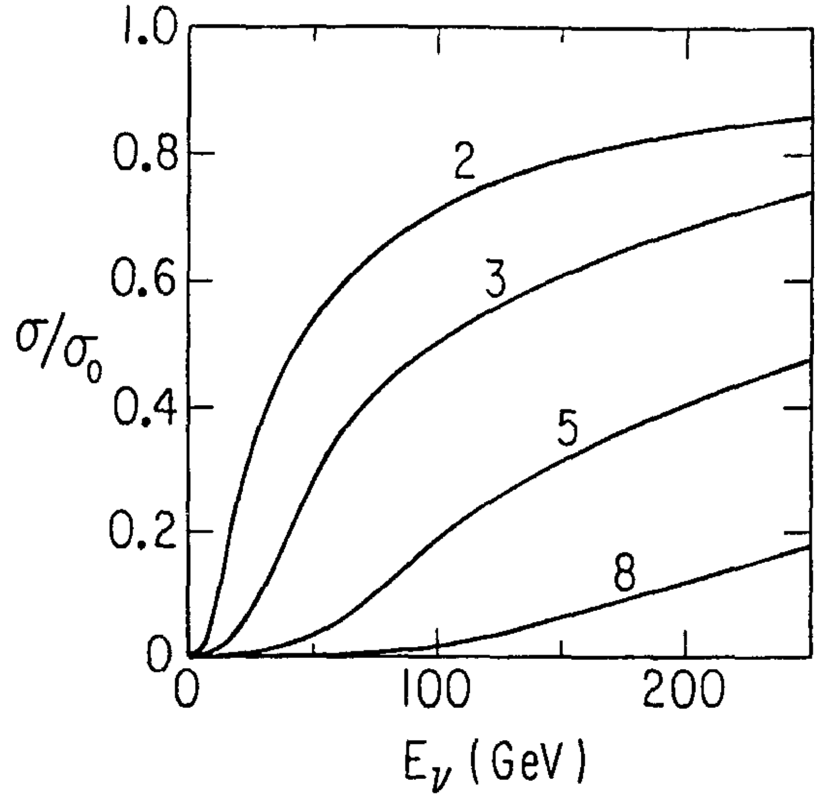

1.0
0.8
0.6
0.4
0.2
0
σ/σ_0
2
3
5
8
0
100
200
E_ν (GeV)

FIG. 13

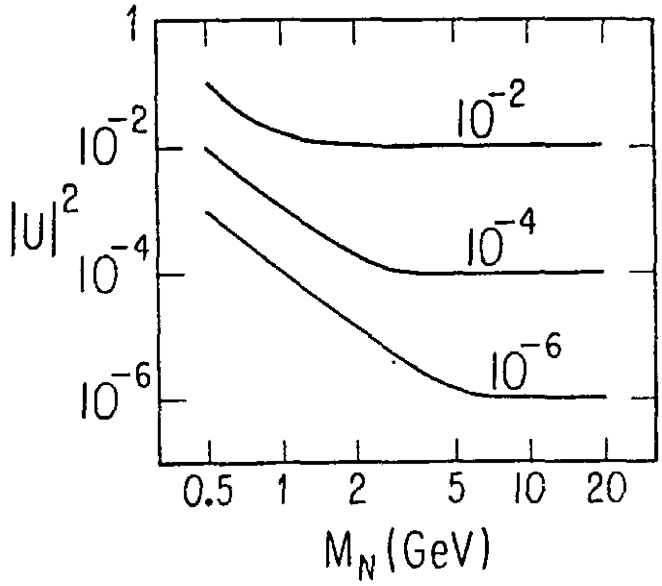

1
10^{-2}
10^{-4}
10^{-6}
$|U|^2$
10^{-2}
10^{-4}
10^{-6}
0.5
1
2
5
10
20
M_N (GeV)

FIG. 14

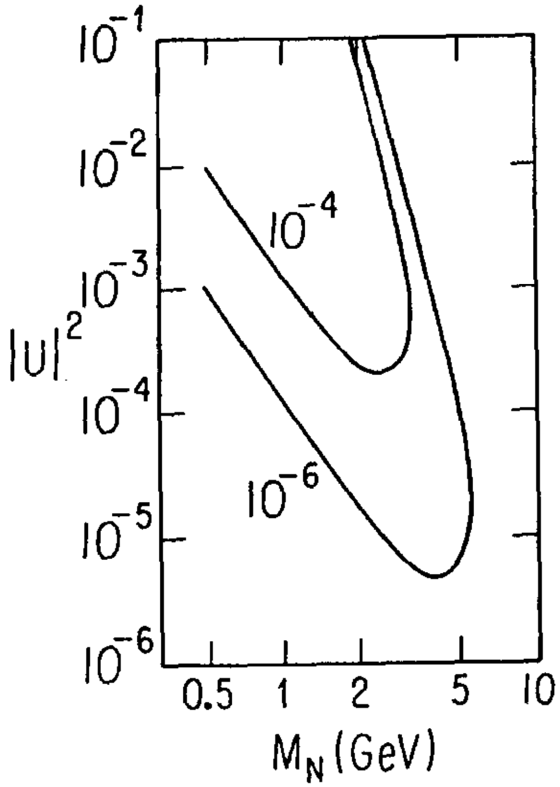

10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$|U|^2$
10^{-4}
10^{-6}
0.5
1
2
5
10
M_N (GeV)

FIG. 15

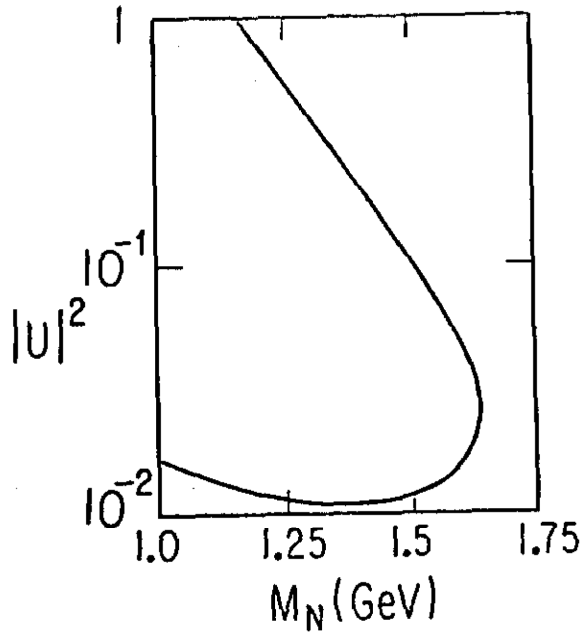

1
10^{-1}
10^{-2}
$|U|^2$
1.0
1.25
1.5
1.75
M_N (GeV)

FIG. 16

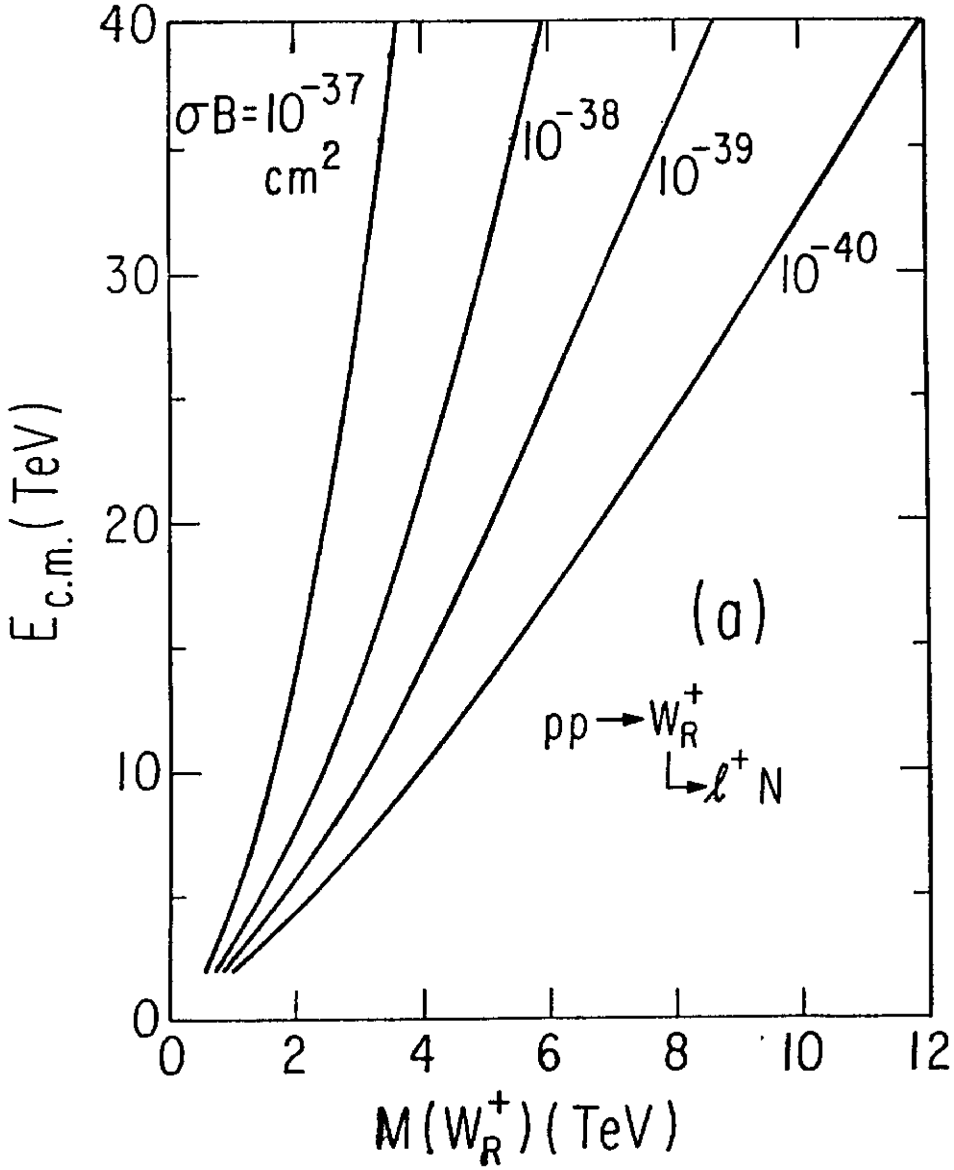


FIG. 17a

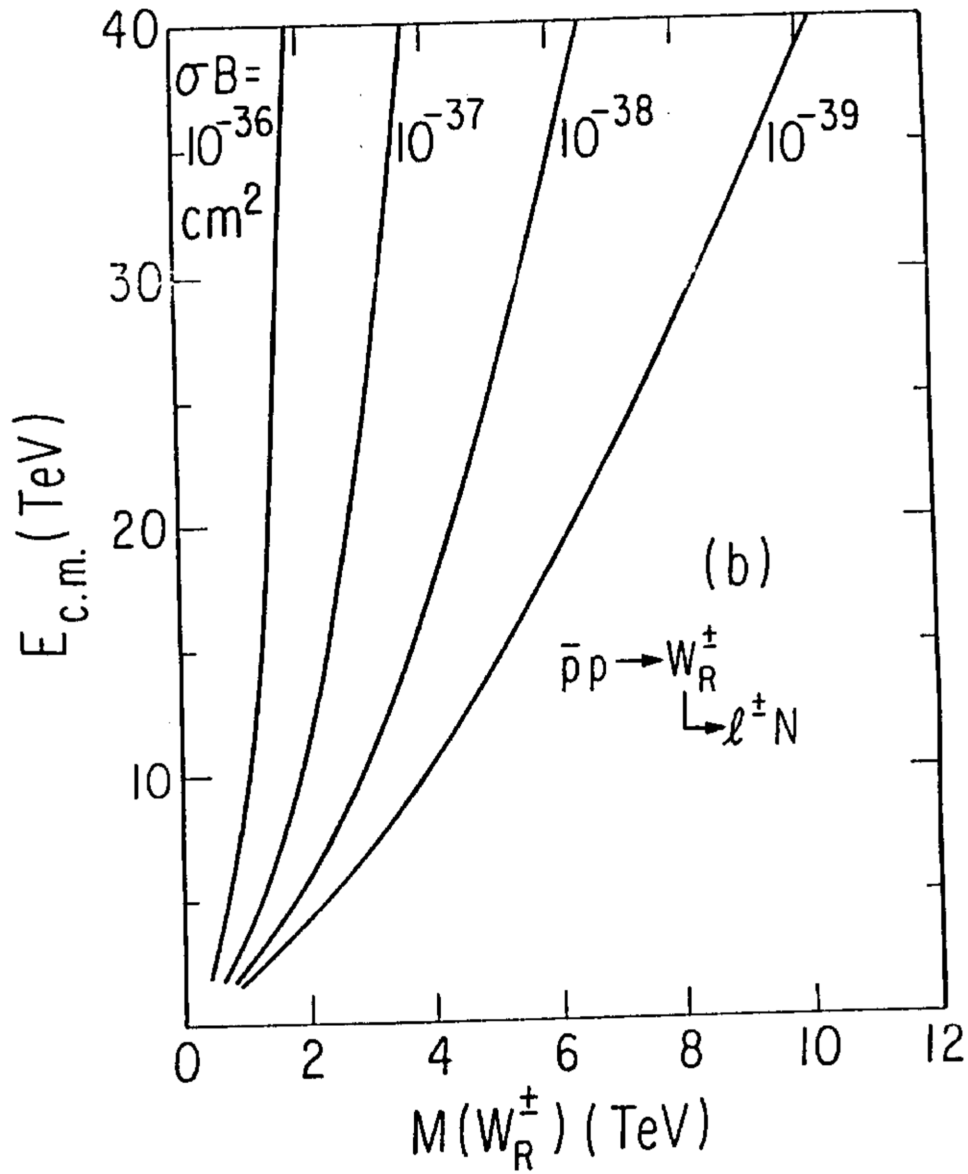


FIG. 17b

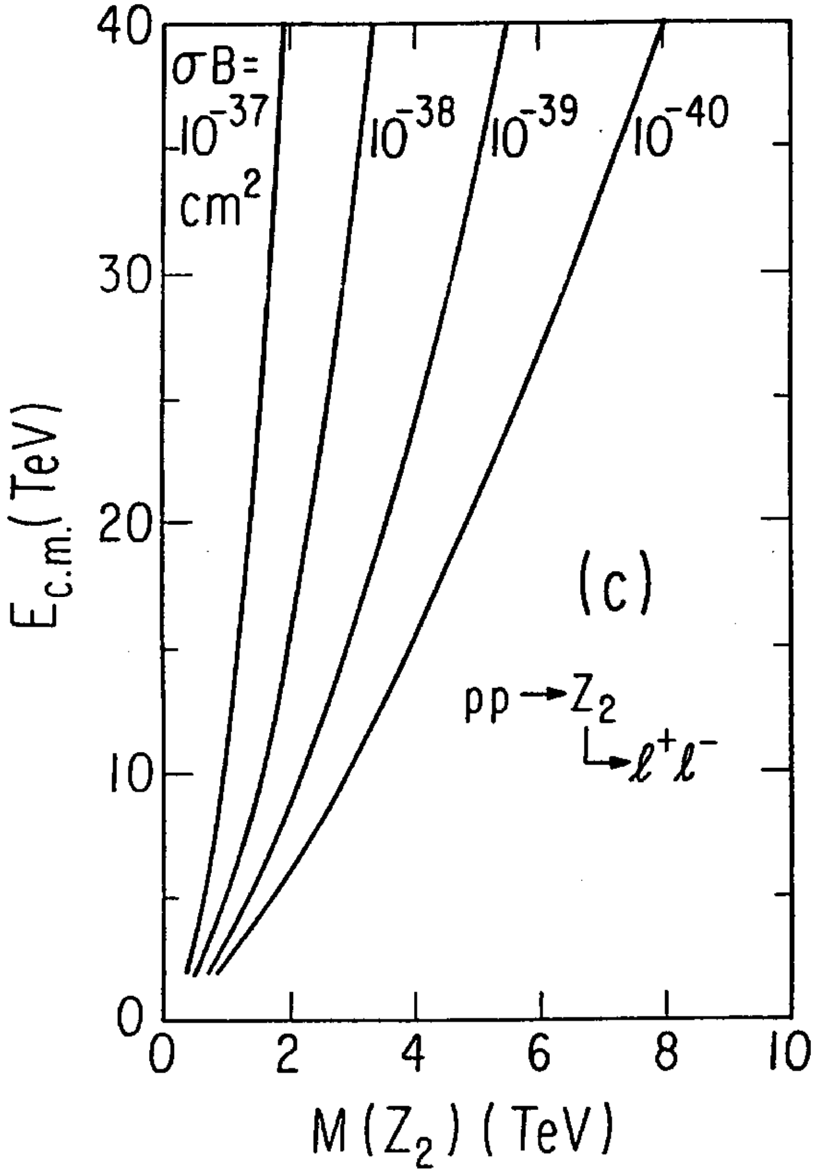


FIG. 17c

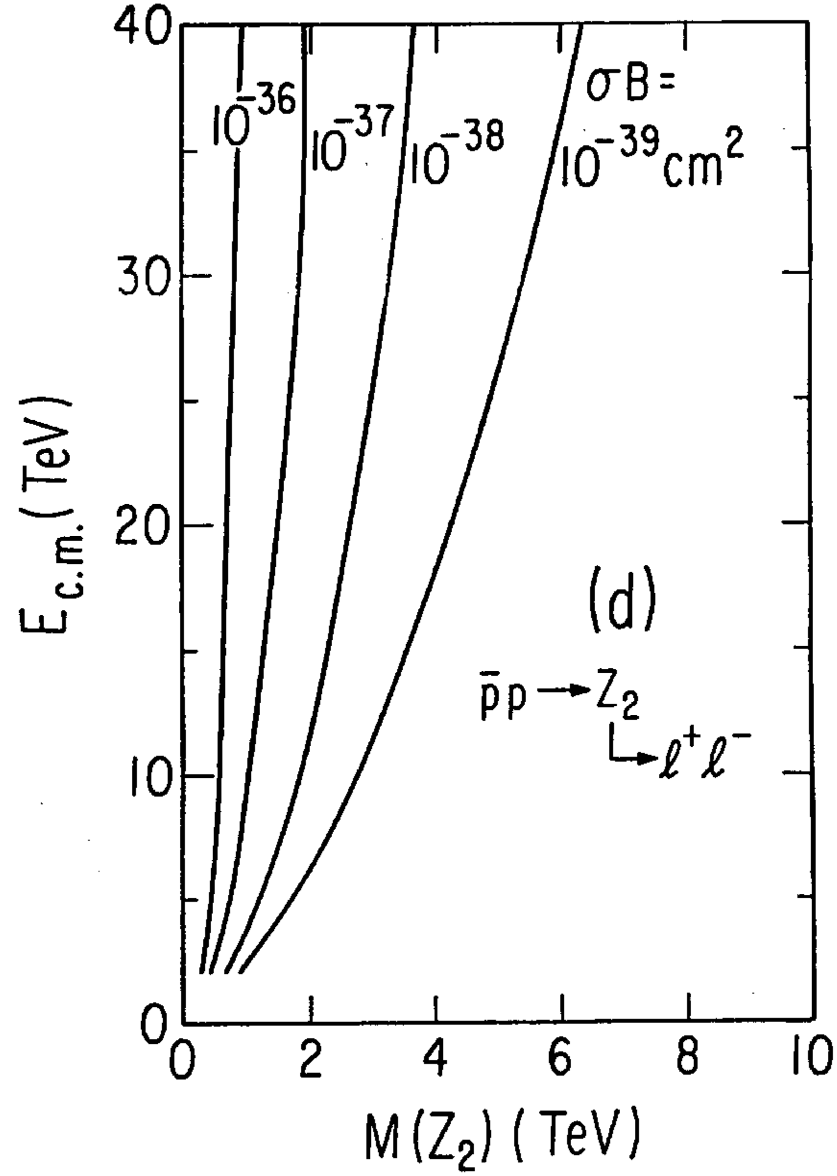


FIG. 17d